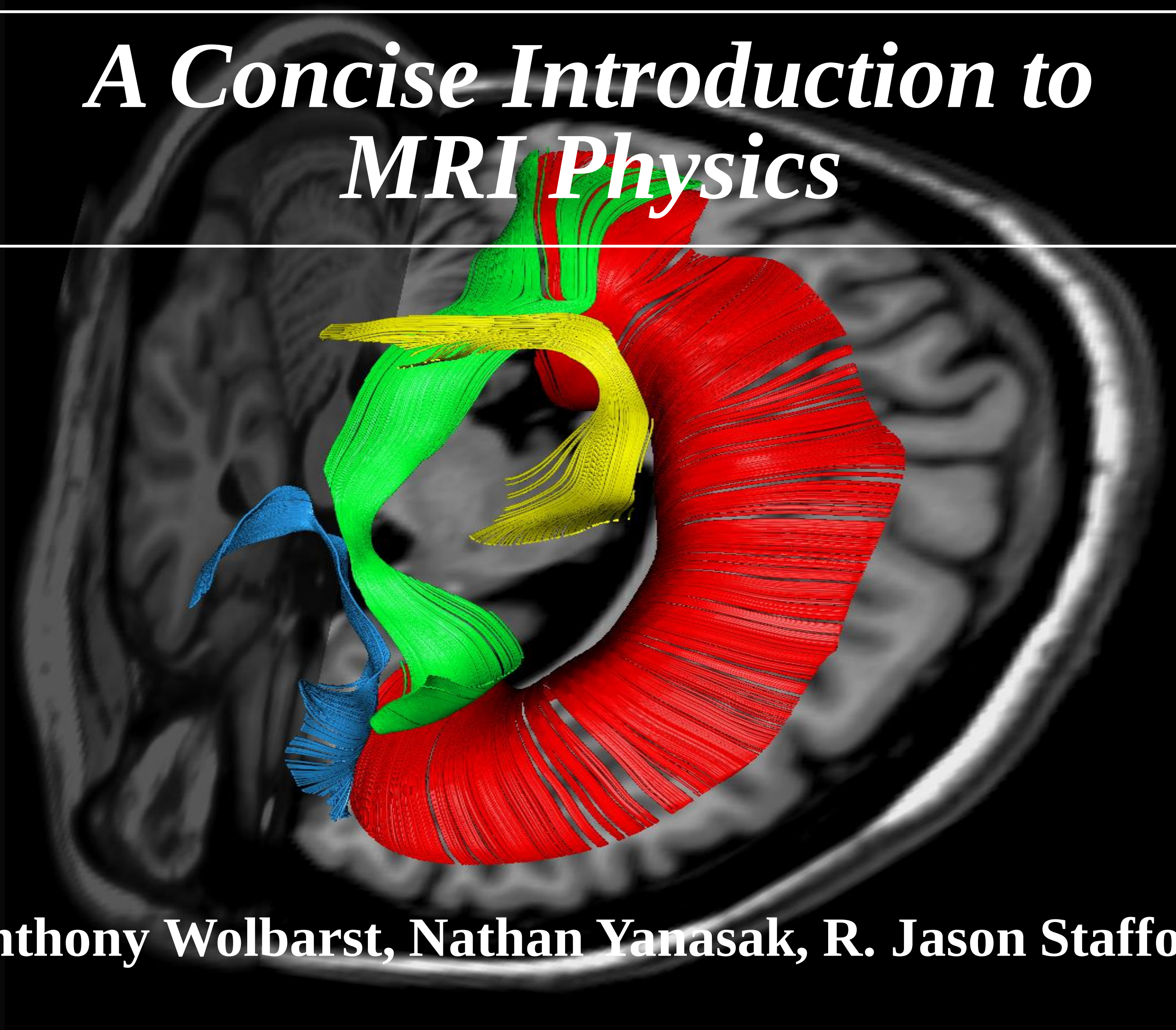
A Concise Introduction to MRI Physics



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Outline for Today

1\.

Introduction to MRI

'Quantum' NMR and MRI in 0D

Magnetization, $\boldsymbol{m}(x,t)$, in a Voxel

Proton Density MRI in 1D

T1 Spin-Relaxation in a Voxel

MRI Case Study, and *Caveat*

2\.

Sketch of the MRI Device

'Classical' NMR in a Voxel

Free Induction Decay in 1D

3\.

T2 Spin-Relaxation

Spin-Echo Reconstruction in 1D

Tissue Contrast-Weighting in SE

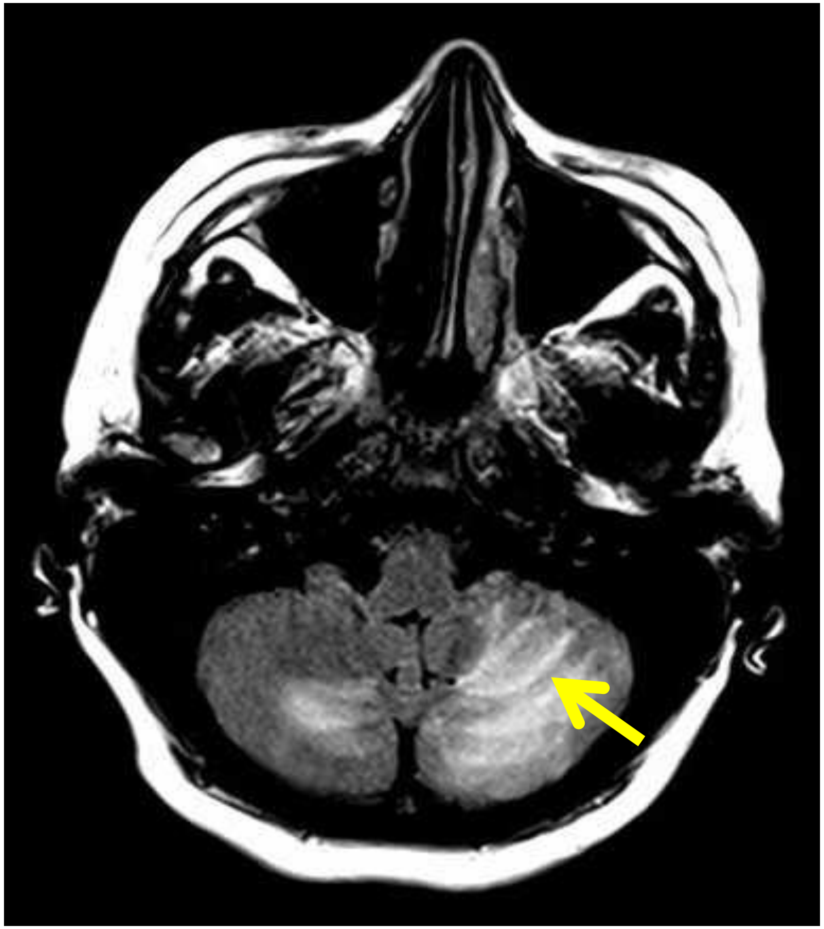
Spin-Echo / Spin-Warp in 2D

Introduction to MRI

Soft Tissue Contrast: CT *vs*. MRI

posterior reversible encephalopathy syndrome (PRES): edematous changes

CT



MRI

Magnetic Resonance Imaging

Yields distinct spatial maps of anatomy, physiology, and pathology of soft tissues.

Multiple unique types of ***contrast*** – created through, and informing on, subtle aspects of tissue biophysics.

No ionizing radiation.

Risks from intense magnetic fields, RF power.

Expensive.

Technology complex, challenging to learn.

Newtonian Contrast among Apples

Different biophysical sources, sensors

Color

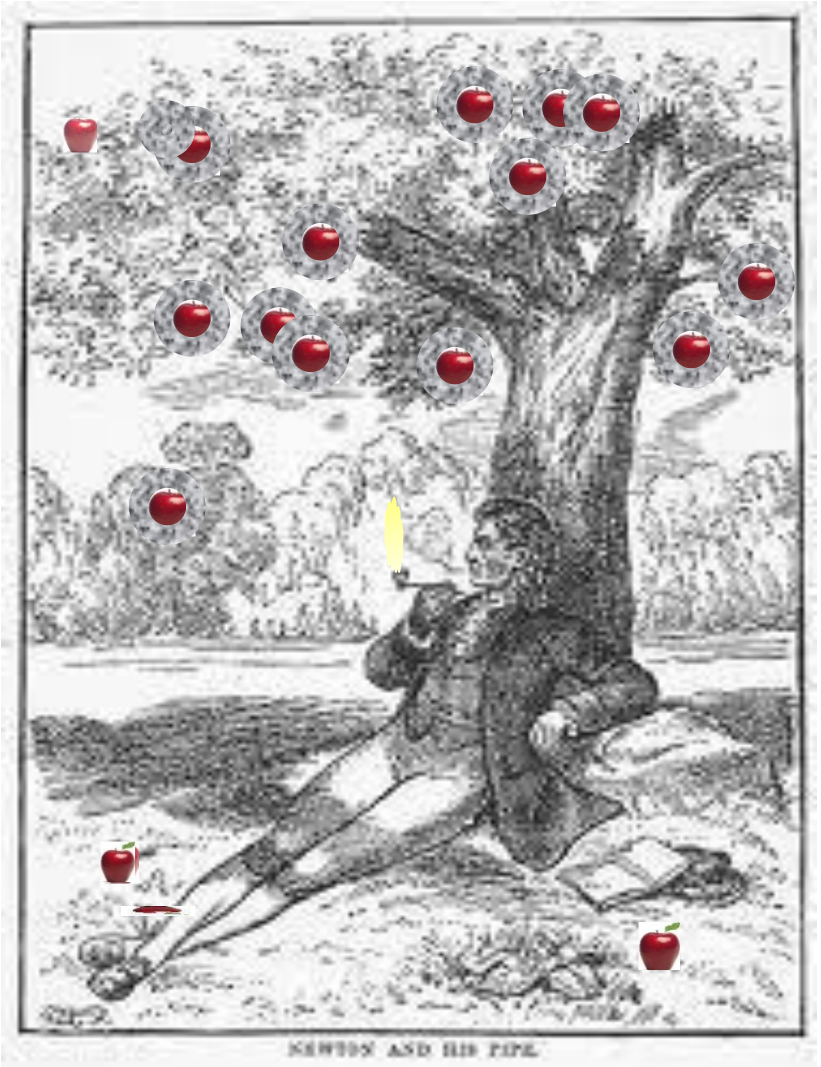
Texture

Smell

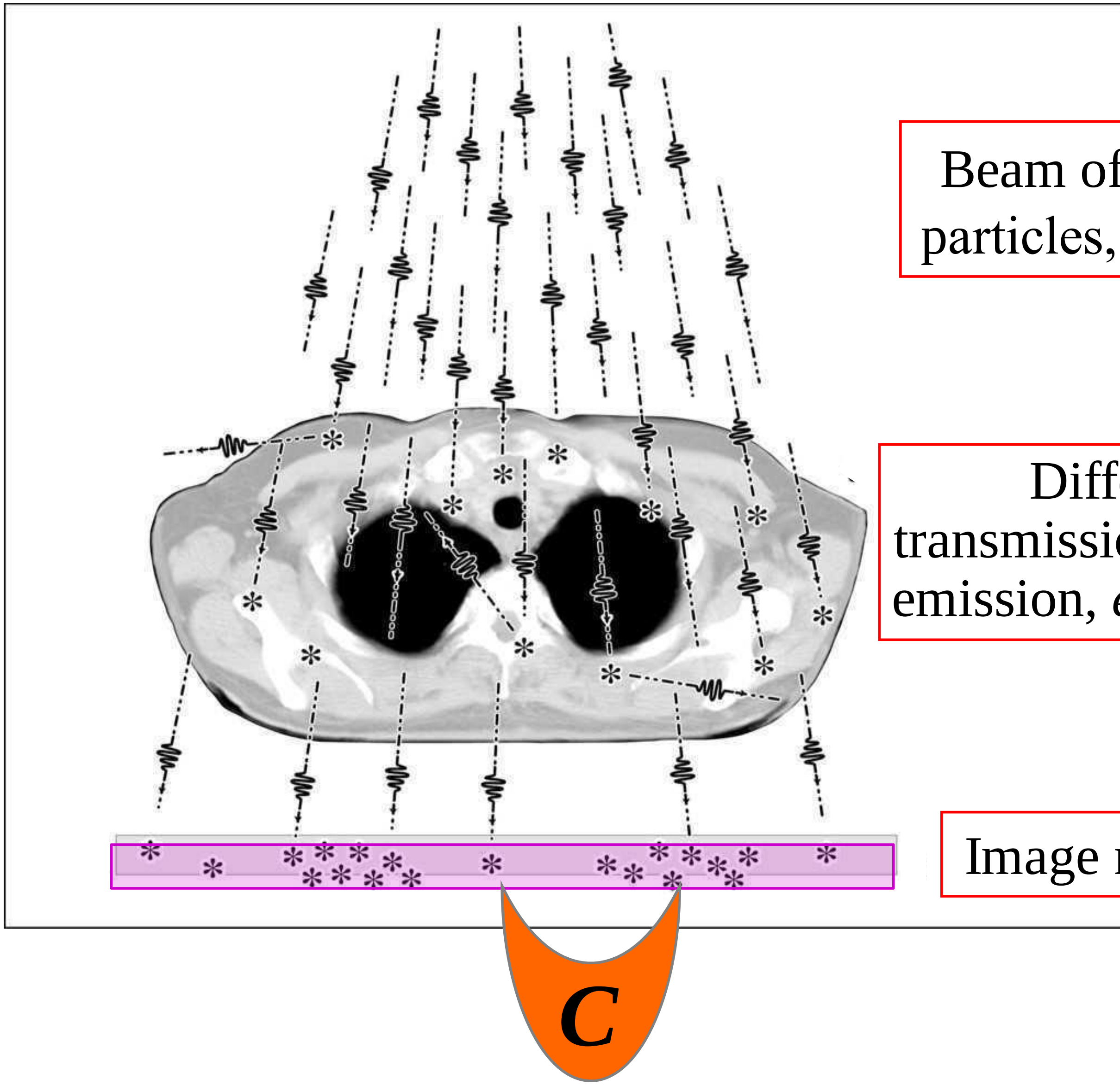
Taste

Holes

etc.



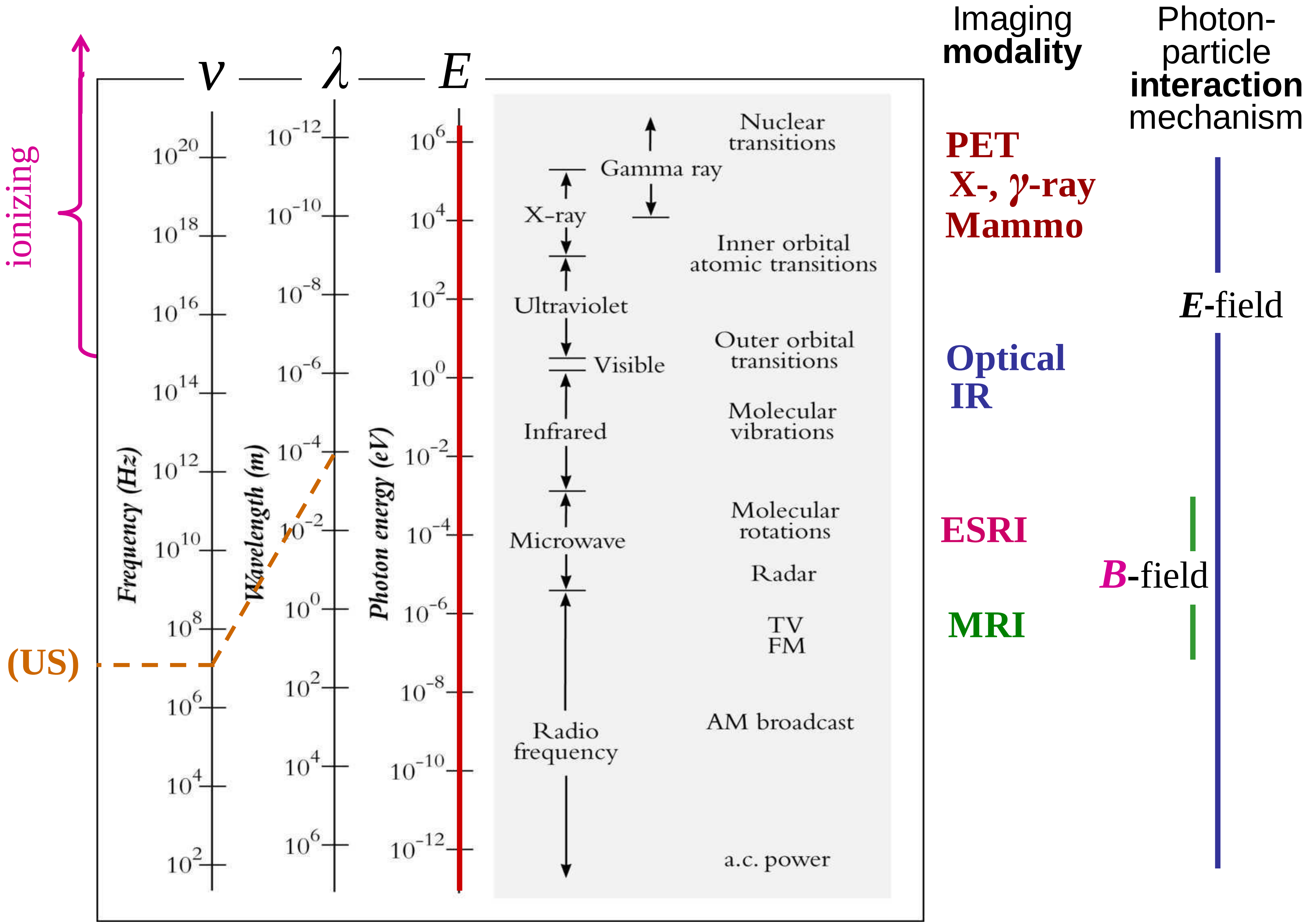
Medical Imaging Contrast



Beam of ***probes***:
particles, waves,…

Differential
transmission, reflection,
emission, *etc*., of probes

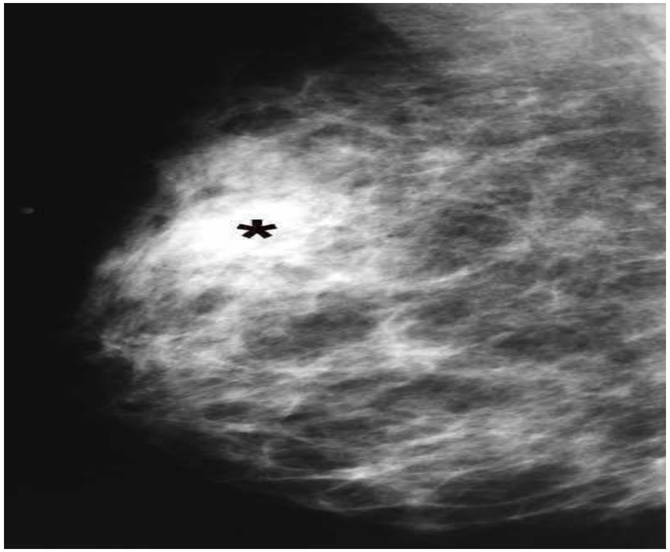
Image receptor


ionizing
(US)
ν
λ
E
Frequency (Hz)
Wavelength (m)
Photon energy (eV)
10^20
10^18
10^16
10^14
10^12
10^10
10^8
10^6
10^4
10^2
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
10^0
10^2
10^4
10^6
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
Gamma ray
X-ray
Ultraviolet
Visible
Infrared
Microwave
Radio frequency
Nuclear transitions
Inner orbital atomic transitions
Outer orbital transitions
Molecular vibrations
Molecular rotations
Radar
TV
FM
AM broadcast
a.c. power
Imaging modality
PET
X-, γ-ray
Mammo
Optical
IR
ESRI
MRI
Photon-particle interaction mechanism
E-field
B-field

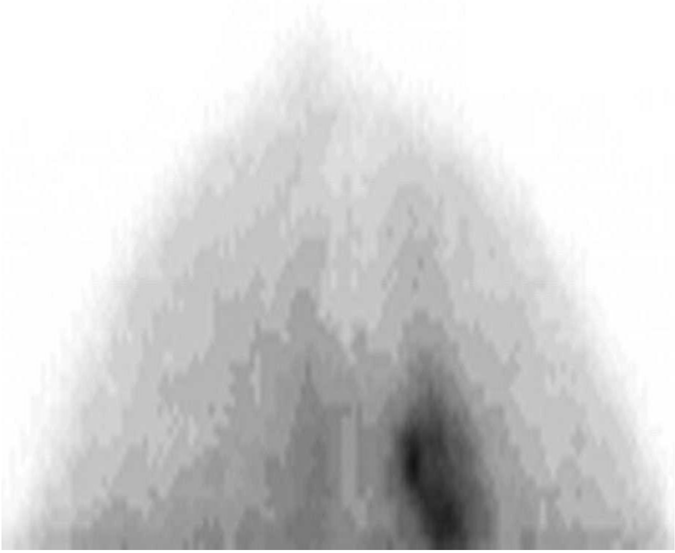
Operation of Imaging Modalities

Modality	Probe / Signal	Detector	Source of *Contrast*: Differences in…
Planar R/F X-ray CT	X-rays transiting the body	AMFPI, II+CCD, GdO, *etc.*, array	$\int_s \boldsymbol{\mu}(\rho, Z, \mathrm{kVp})\, ds$
Nuc Med, SPECT, PET	Gamma-rays, 511 keV emitted	NaI single crystal; multiple NaI; LSO array	Radiopharmaceutical uptake, concentration ^{99m}Tc, ^{18}FDG,…
US	MHz sound, reflected	Piezoelectric transducer	$\rho,\ \kappa,\ \mu_{\mathrm{US}}$
MRI	Protons, photons probe mol. mag. environments	RF radio receiver coils	T1, T2, PD, [O], blood flow, water diffusion, chemical shift,…

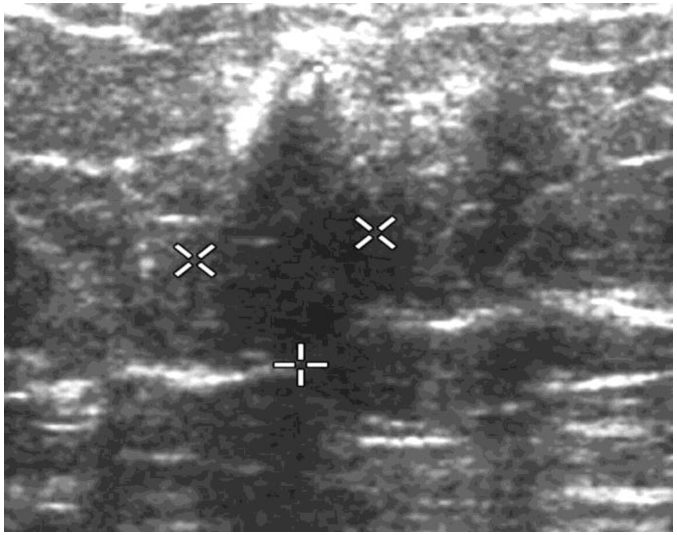
Standard Breast Modalities



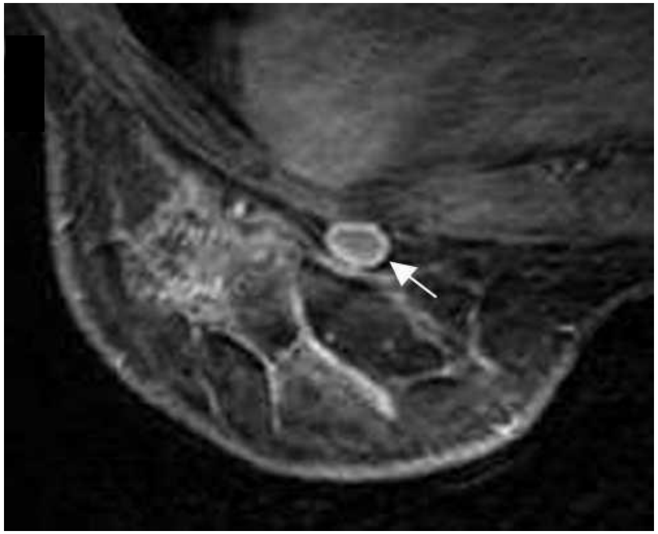
Mammography



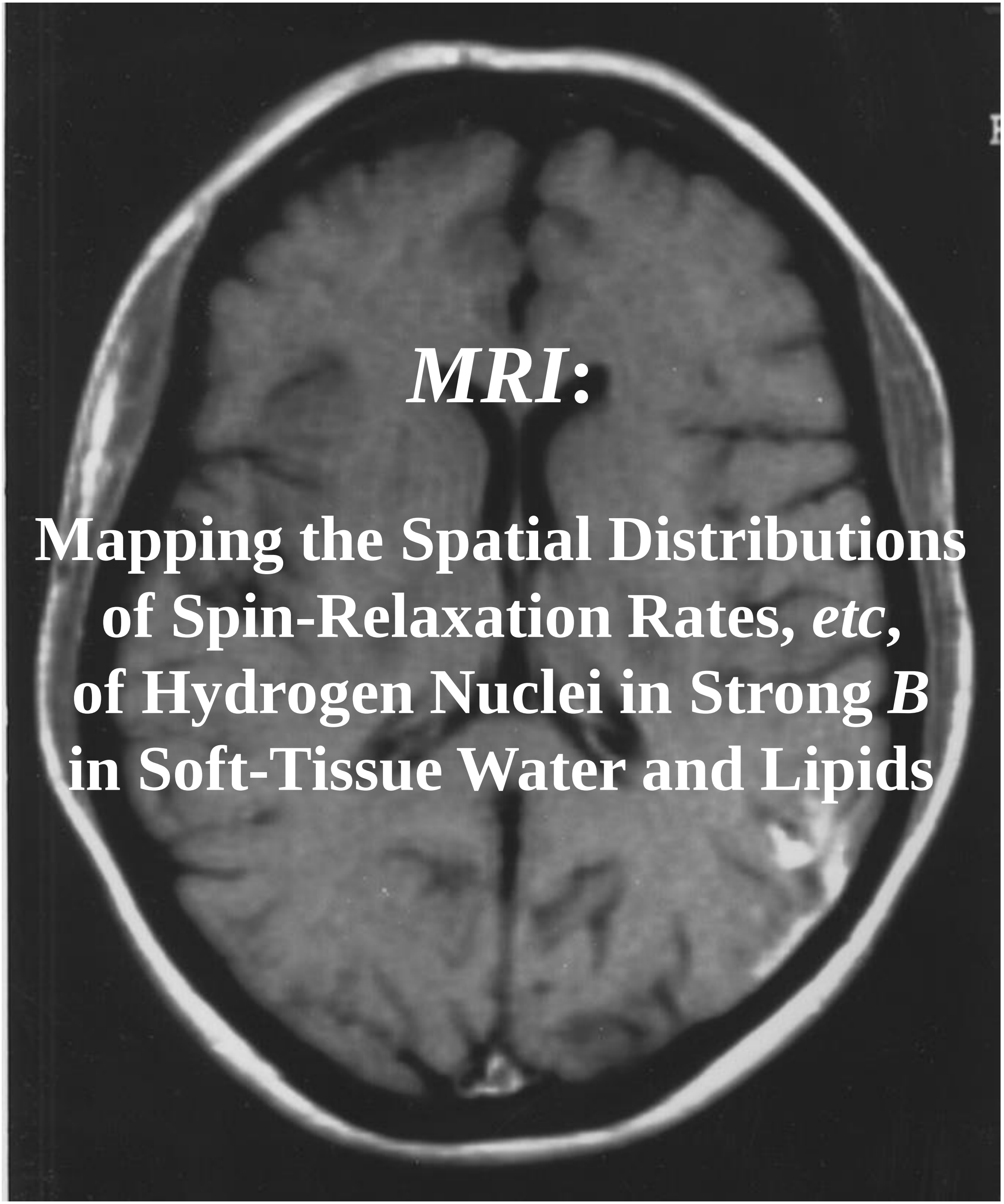
PET



Ultrasound



MRI



MRI:

Mapping the Spatial Distributions of Spin-Relaxation Rates, *etc*, of Hydrogen Nuclei in Strong *B* in Soft-Tissue Water and Lipids

Put Another Way…

Soft-Tissue Water and Lipids
Hydrogen Nuclei in B_0
Spin-Relaxation Rates, *etc*.,

} ***NMR***

Spatial Distributions ***MRI***

‘Quantum’ NMR and MRI in 0D

Two Approaches to Proton NMR/MRI (*incompatible!*)

$|\psi\rangle$

Simplified QM | *Full QM*

Up/down spin states

$|\uparrow\rangle$, $|\downarrow\rangle$

transitions between the two spin states

$\boldsymbol{v}_{\mathrm{Larmor}}$, $\boldsymbol{m}_0$, T1

Classical Bloch Eqs.

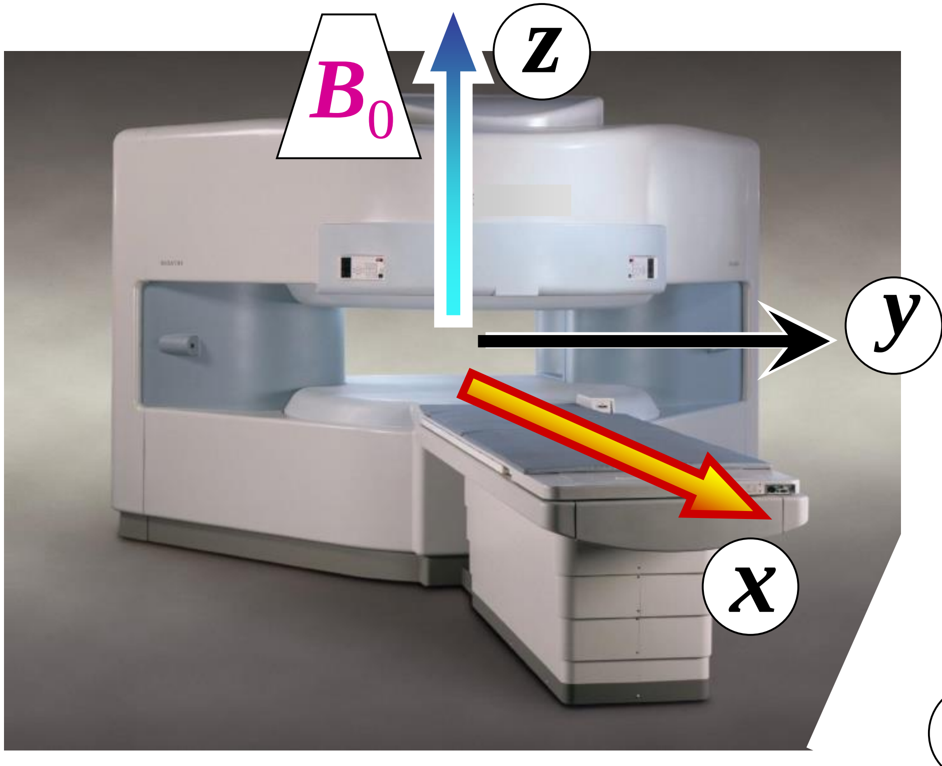
for $\langle \boldsymbol{m}(t) \rangle$

precession, nutation of magnetization

$\boldsymbol{v}_{\mathrm{Larmor}}$, T2, $\boldsymbol{k}$-space, 2D

MRI Magnets

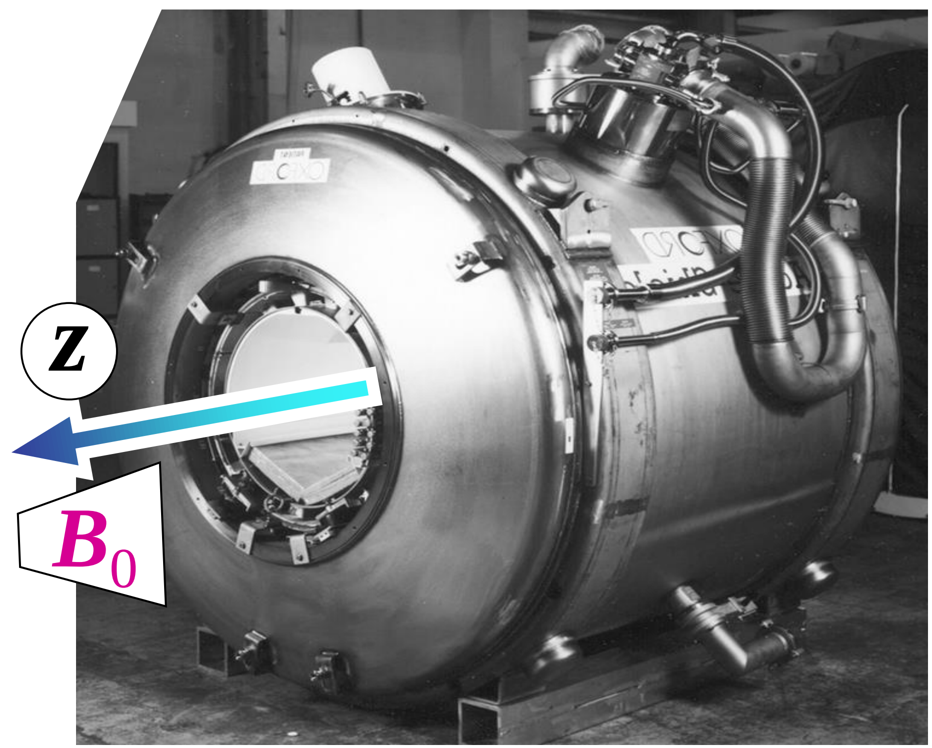
principal magnetic field $\boldsymbol{B}_0$ defines $\boldsymbol{z}$-axis



Open: electromagnetic or permanent

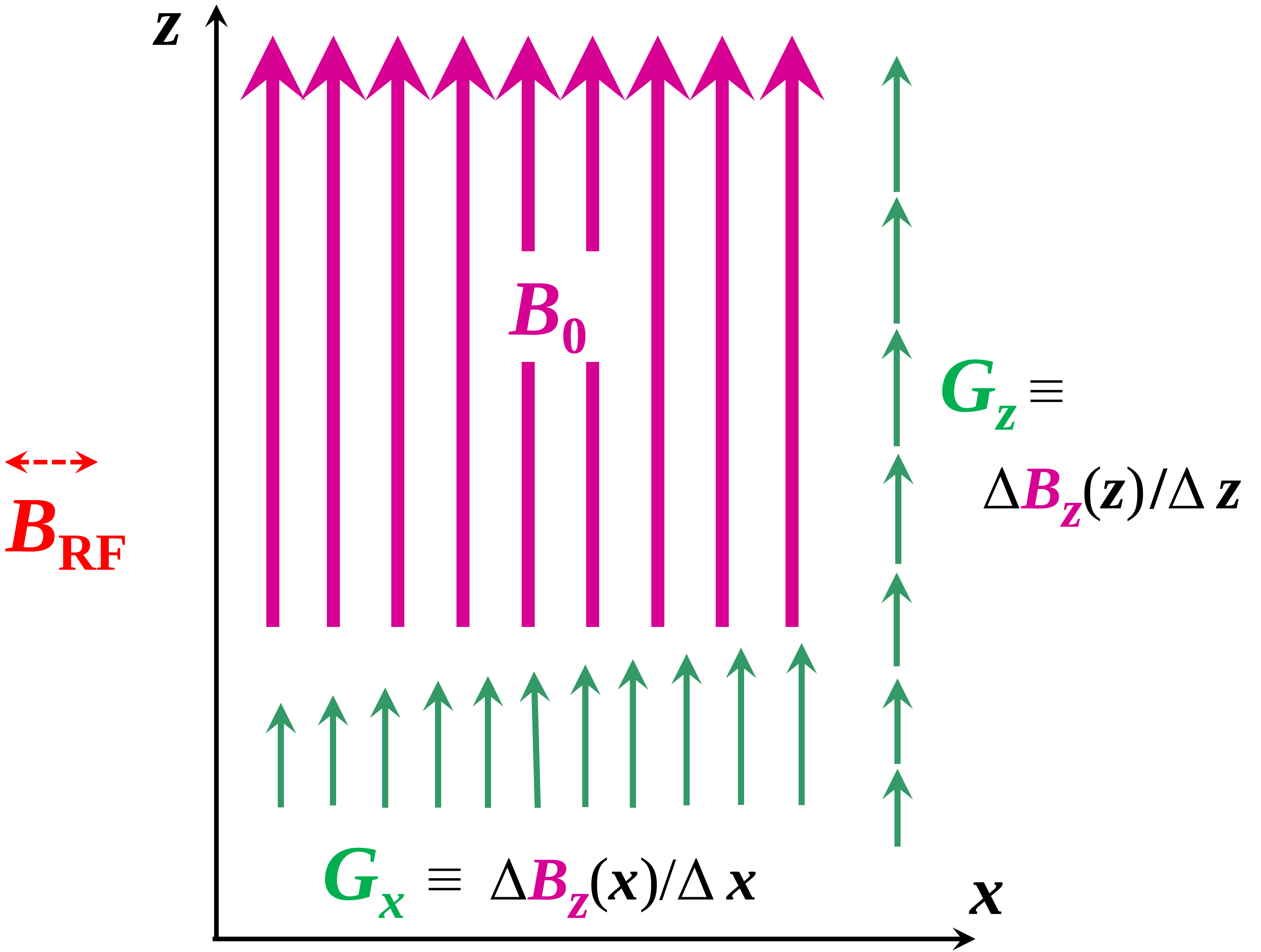
Superconducting:

e.g., niobium-titanium wire



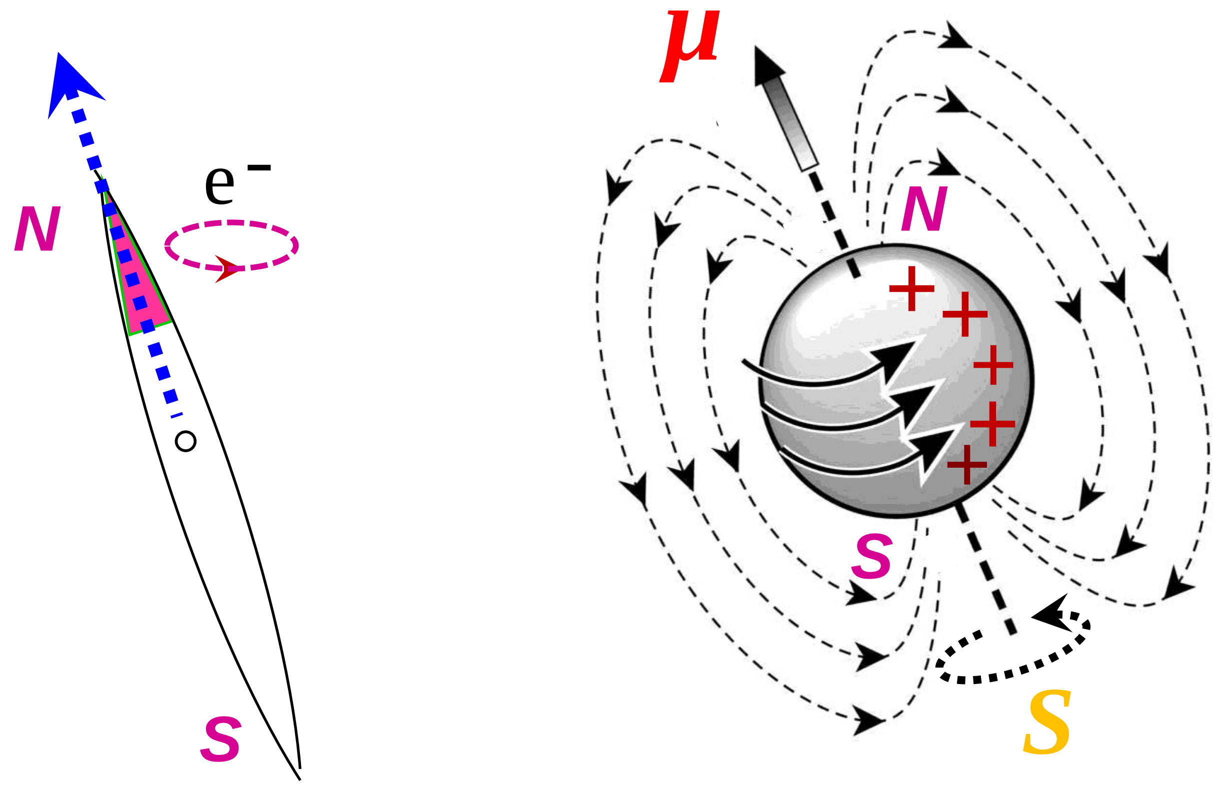
Three External Magnetic Field Types in ***Open***-Magnet MRI

B_0, G_z , and G_x all point along z. Not B_{RF}!

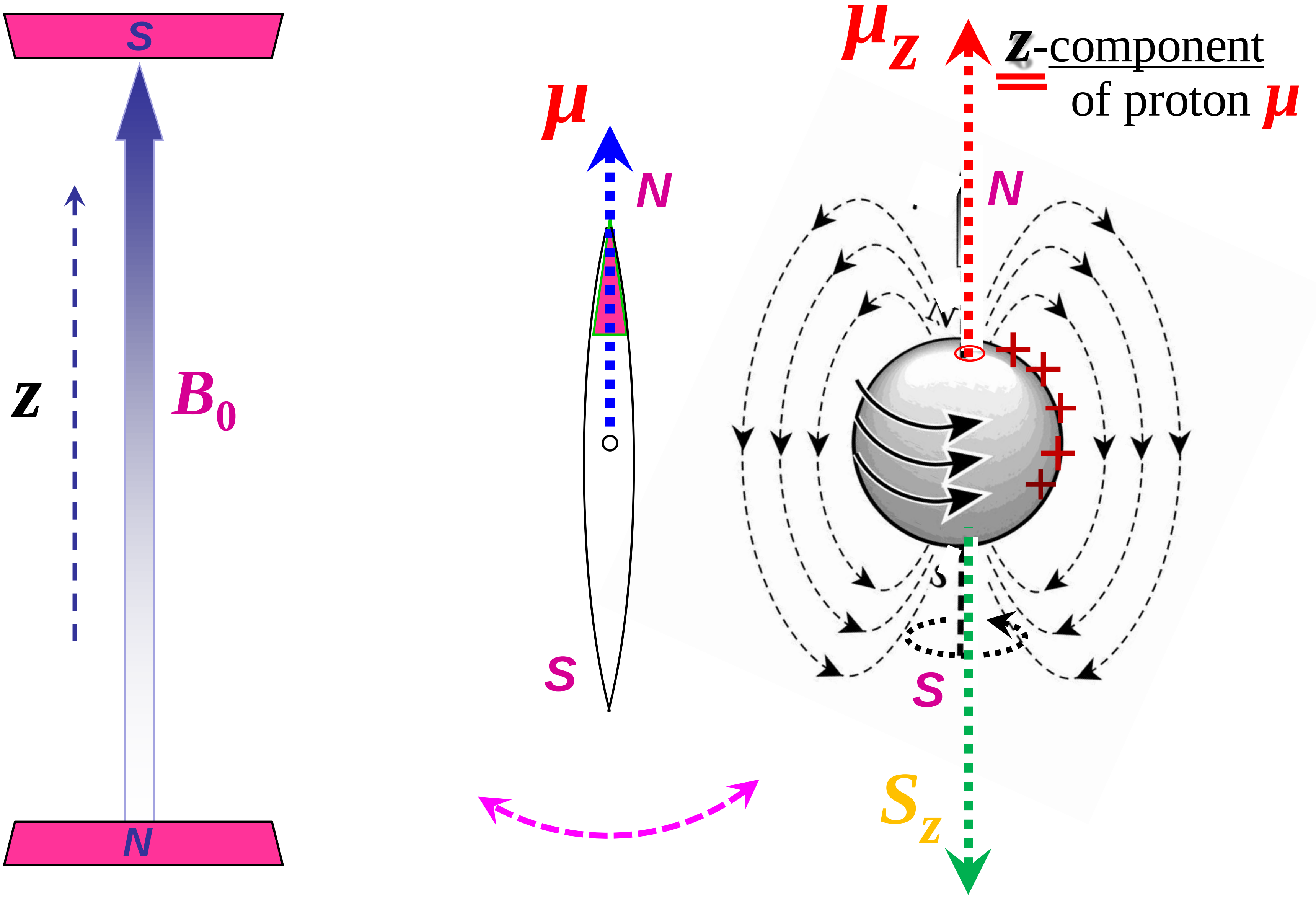


Moving Charge Produces Magnetic Field

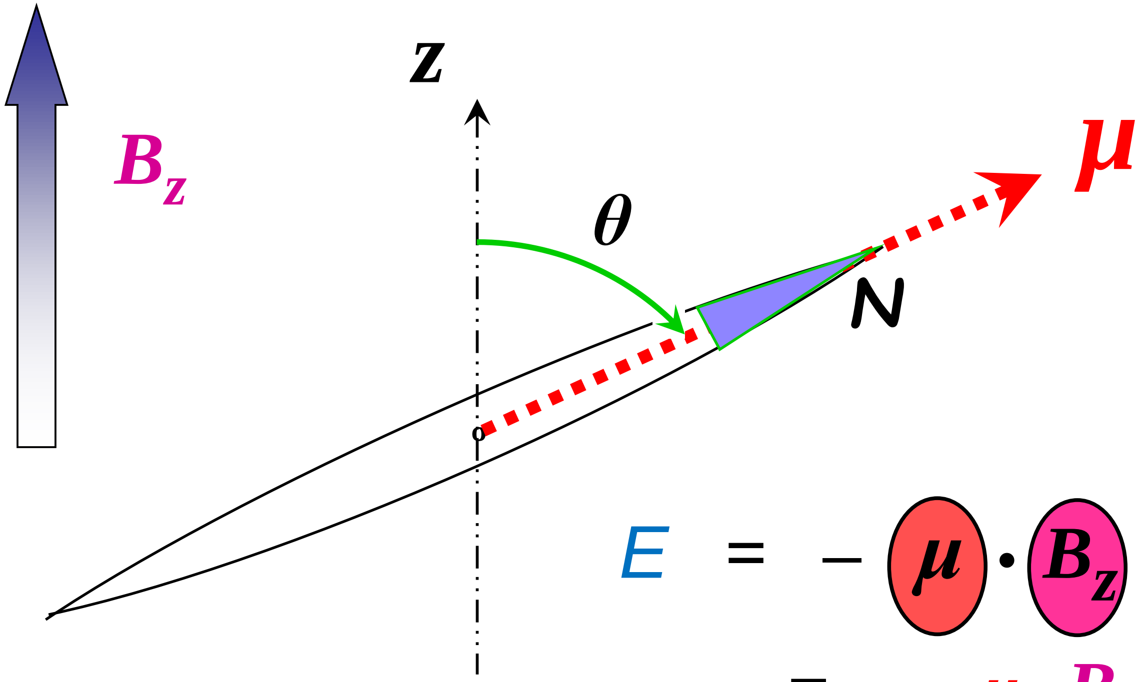
compass needle; proton 'spinning' on axis



Magnetic Dipole Tends to Align in *External* Field



Energy to Flip Over Needle with Magnetic Moment $\boldsymbol{\mu}$ in B_z



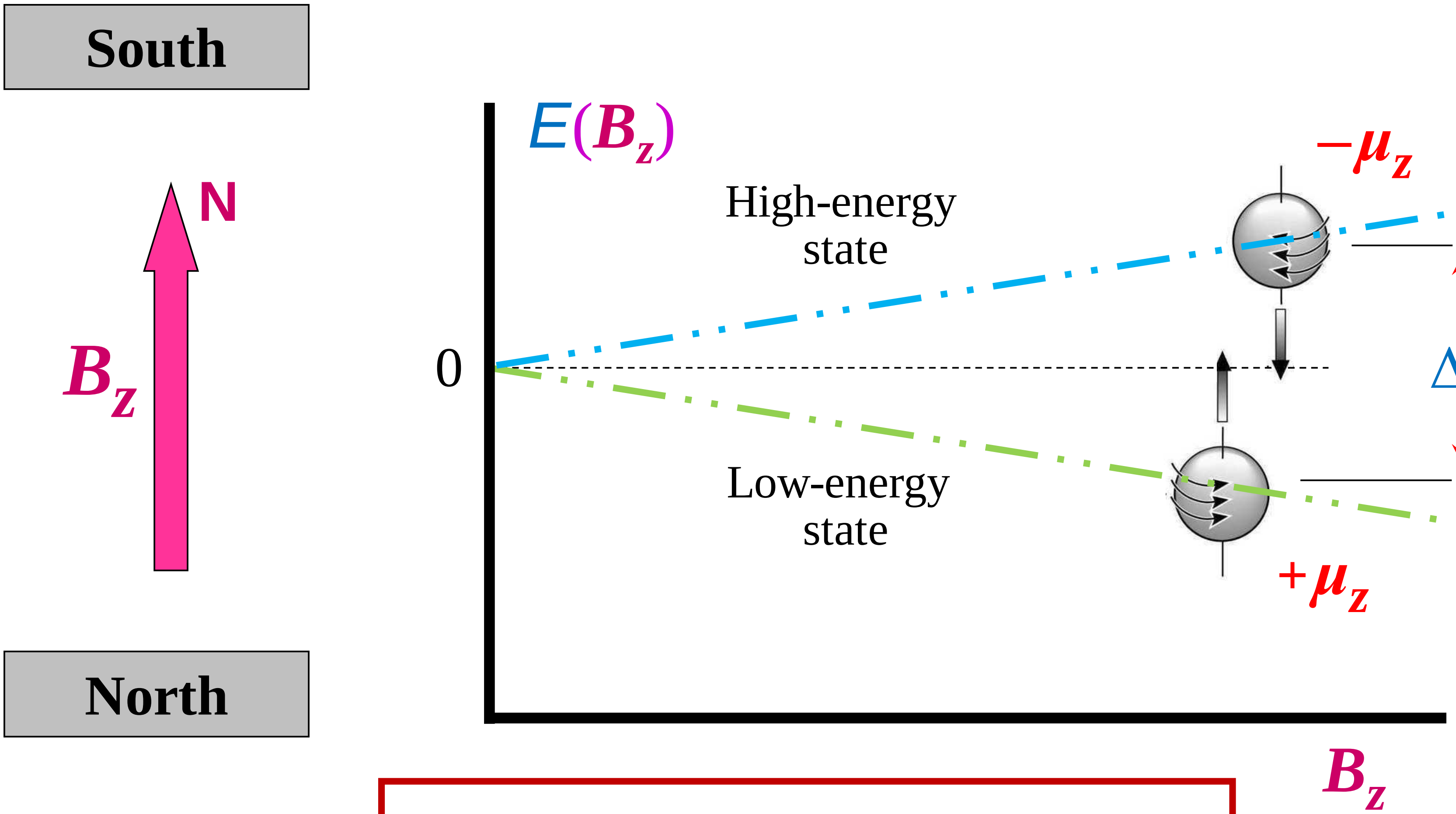
$$E = -\boldsymbol{\mu} \cdot \boldsymbol{B_z}$$

$$= -\mu_z B_z \cos\theta$$

$$\Delta E_{180^o} = \pm 2\,\mu_z B_z$$

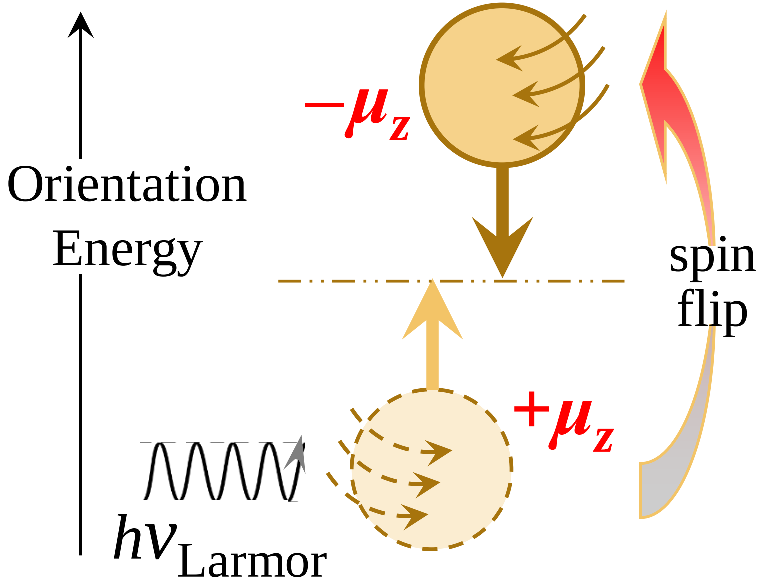
Nuclear Zeeman Splitting for Proton: $\Delta E = \pm 2\, \mu_z B_z$

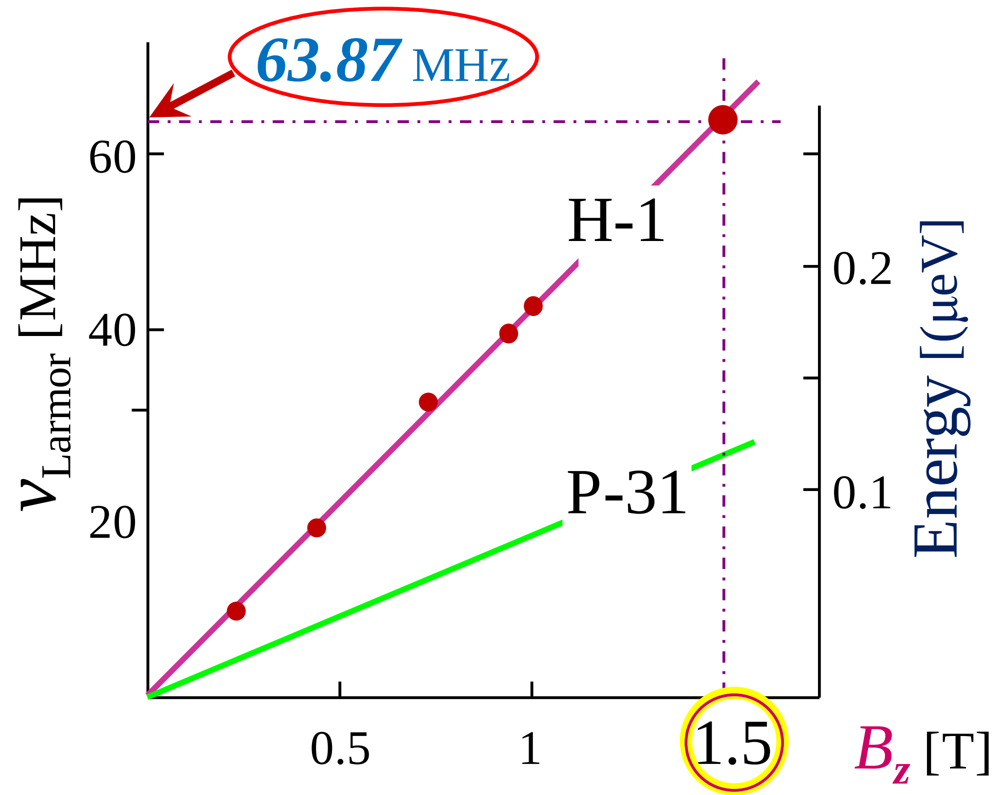
μ_z points only along or against z



$$\Delta E_{180^o}(B_z) = \pm 2\, \mu_z B_z$$

Nuclear Magnetic Resonance: Larmor Frequency





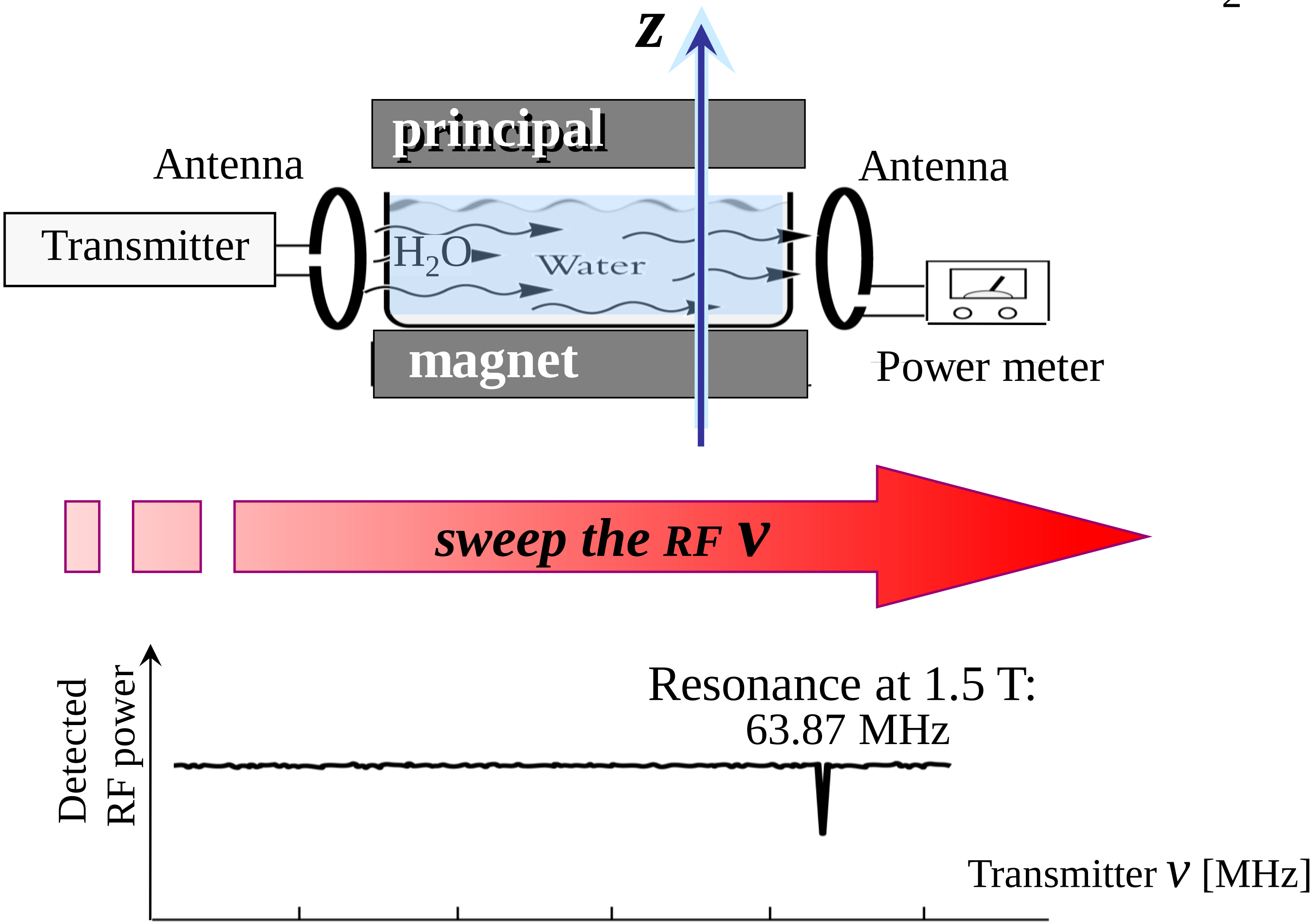
pr**r**oton: $\Delta E_{180°} = 2\,\mu_z B_z$

ph**h**oton $E = h\nu$

$$\nu_{\text{Larmor}}(B_z) = (\gamma/2\pi)\, B_z$$

NMR Gedanken-Experiment on Water

monochromatic RF power absorption at (and only at) $\nu_{\text{Larmor}-H_2O}$



3D Sensitive Point Reconstruction

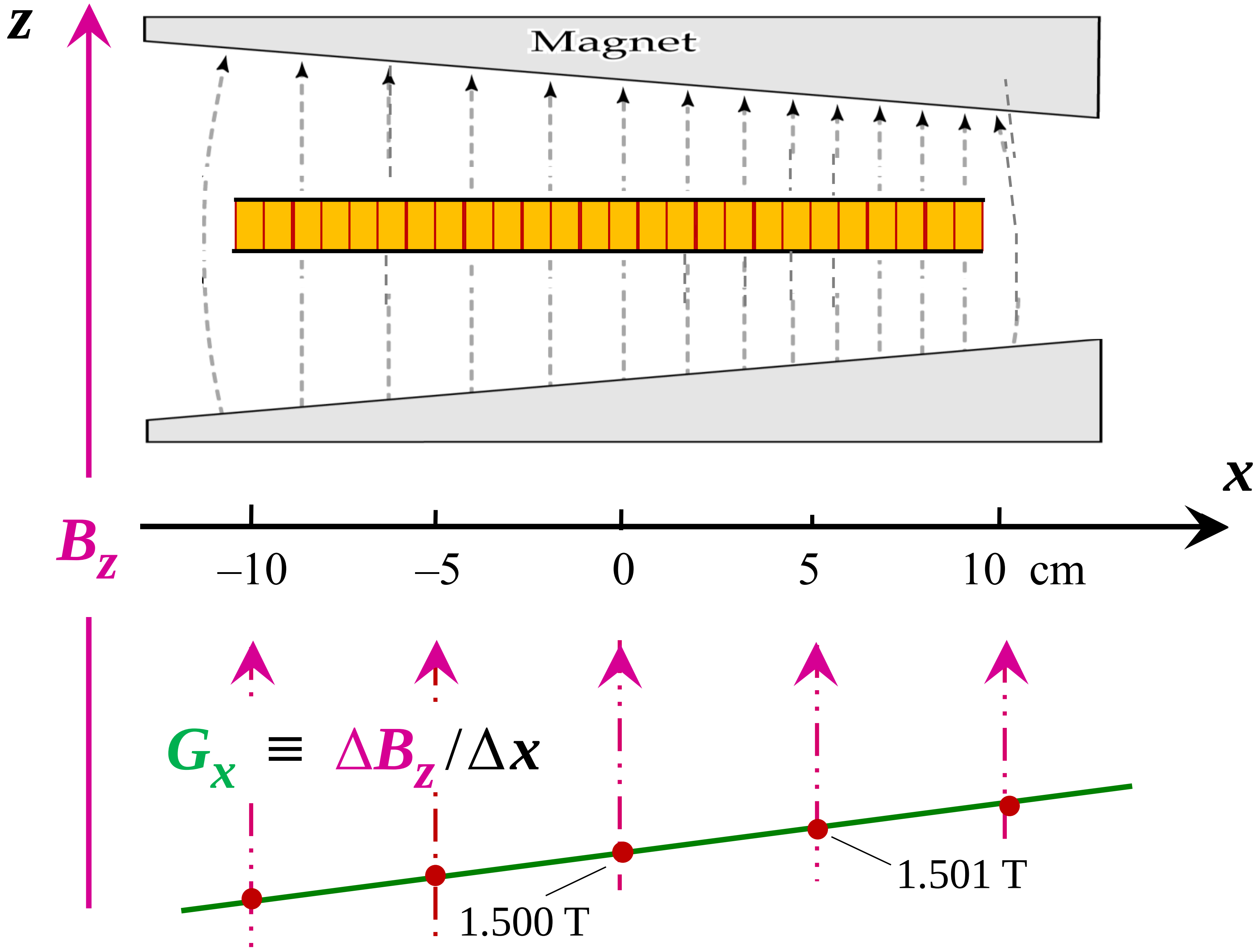
The three gradient fields oscillate wildly,

produce a net field ***stable*** at only one voxel.

NMR occurs there.

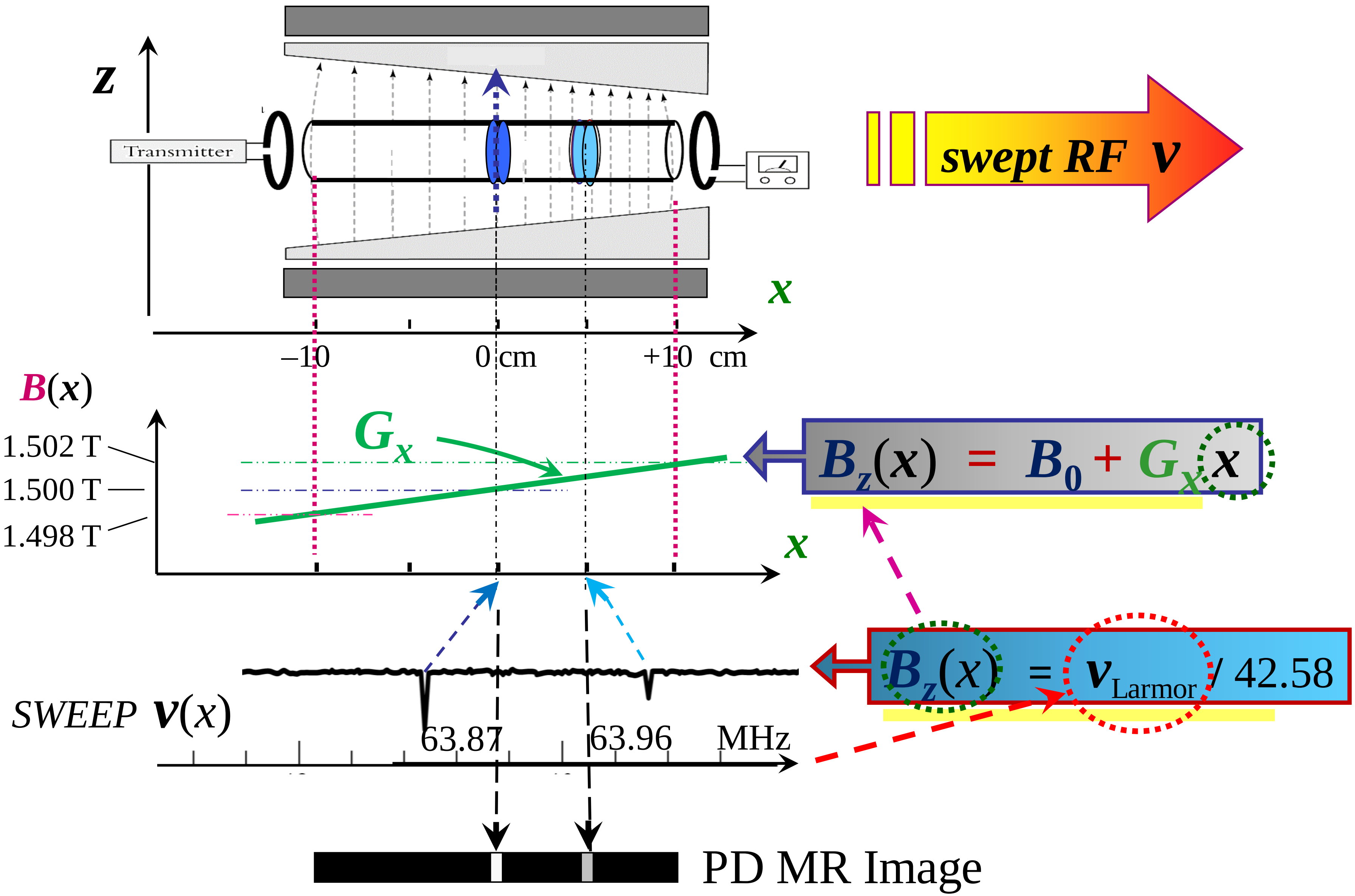
“Sensitive point” then shifts one voxel over.

Proton Density MRI in 1D

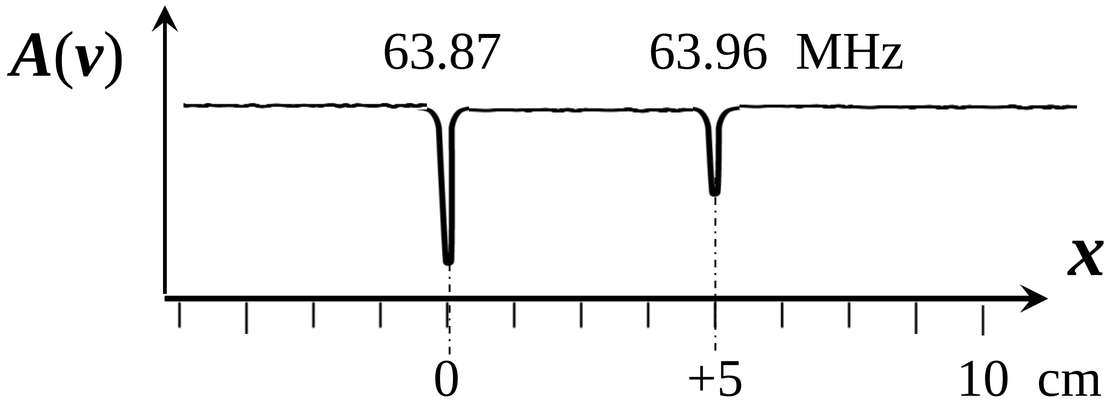


z
Magnet
x
B_z
–10
–5
0
5
10 cm
$G_x \equiv \Delta B_z / \Delta x$
1.500 T
1.501 T

$\nu_{Larmor}(x) \rightarrow B_z(x) \rightarrow x$



Summary: PD MRI on 1D Patient



ν_{Larmor} of NMR Peak

Amplitude of NMR Peak

$B_z(x)$

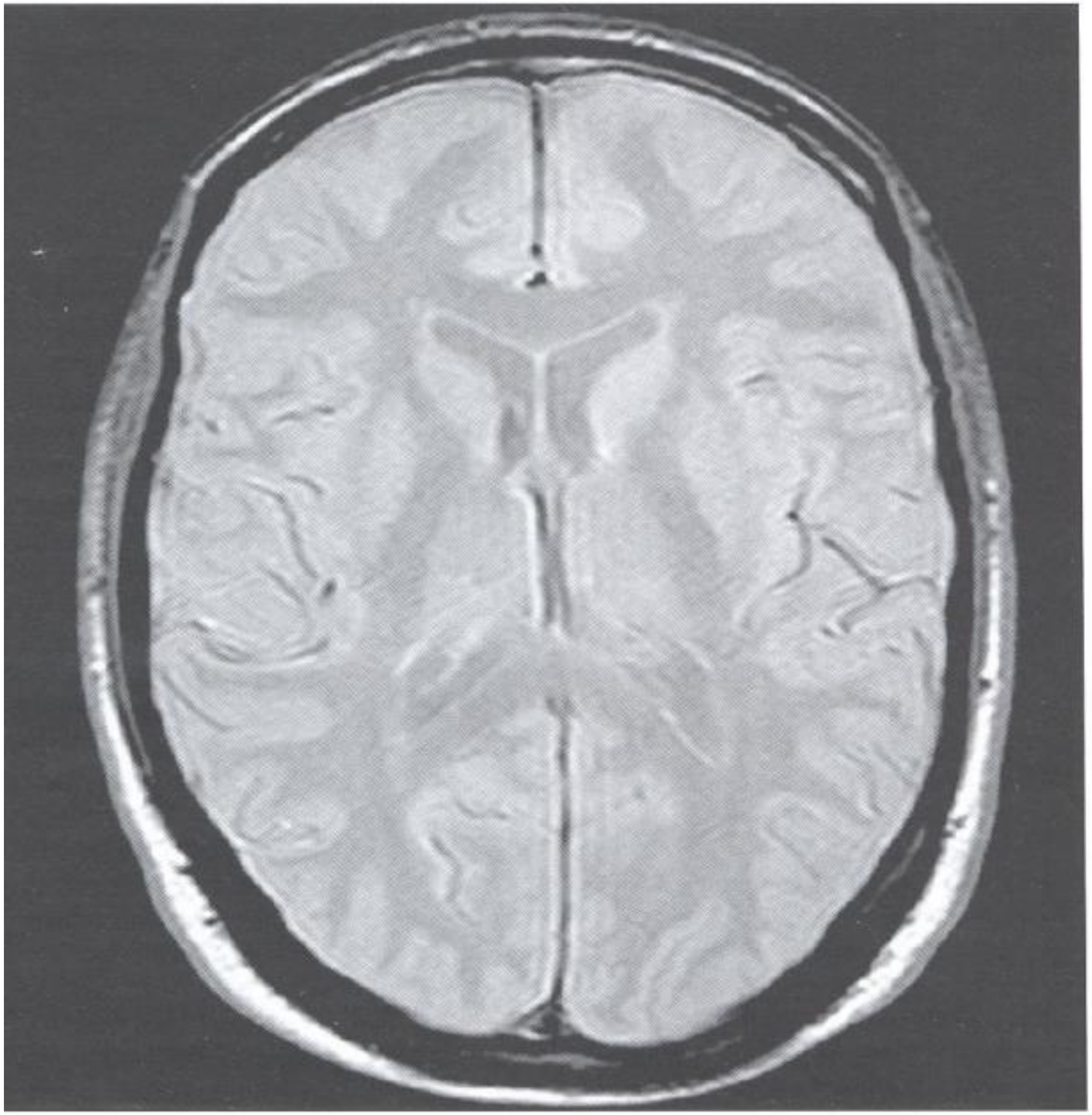
PD(x)

Voxel Position, x

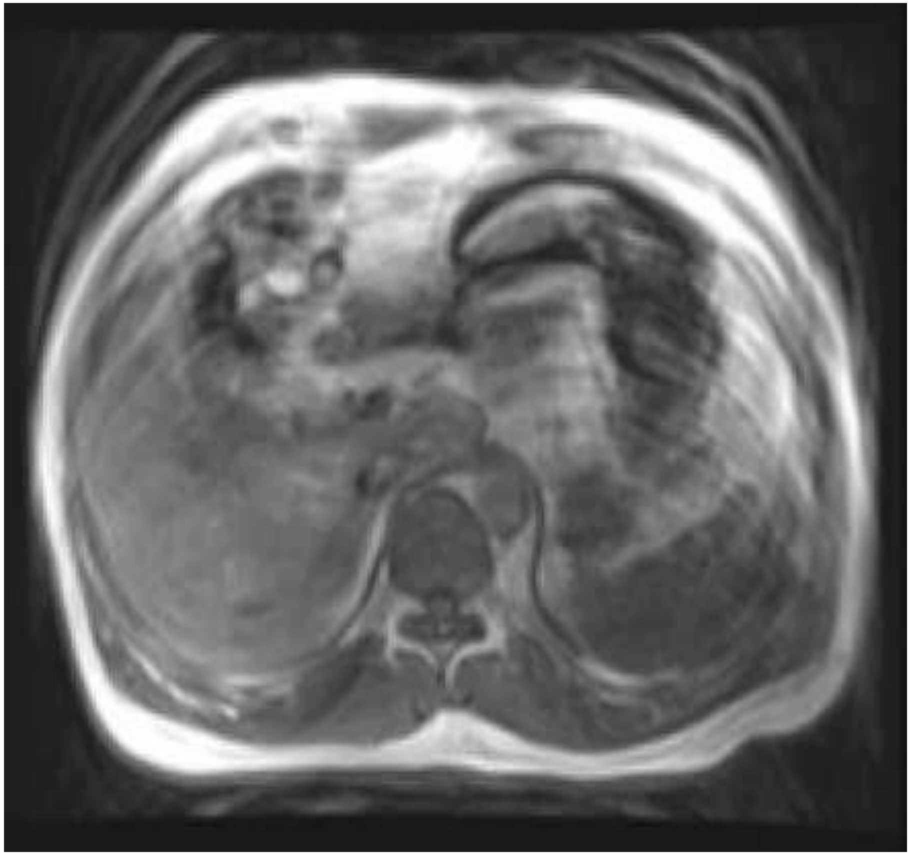
Pixel Brightness, PD

Proton-Density MRI

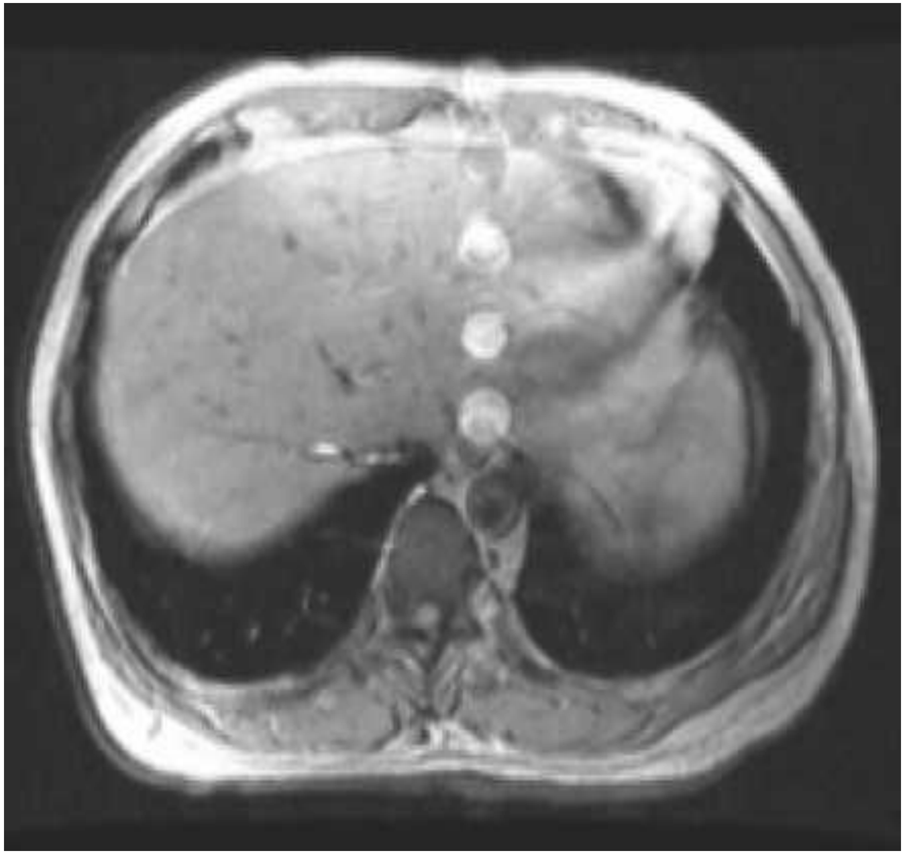
contrast from differences in PD



Two MRI Motion Artifacts



respiration



aortic pulsation

Magnetization, $\boldsymbol{m}(t)$, in a Voxel

Voxel's MRI Signal Proportional to Its Magnetization, $\boldsymbol{m}(x,t)$

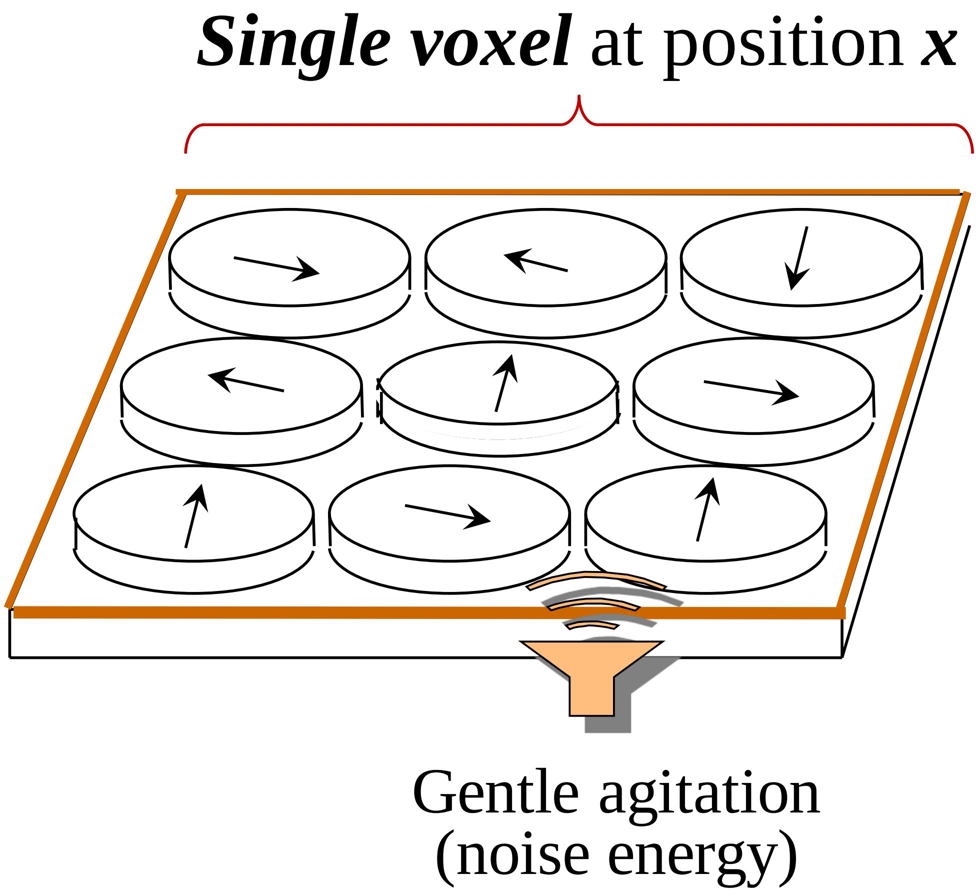
***i*) What is the magnitude of voxel magnetization at dynamic thermal equilibrium, $\boldsymbol{m}_0$?**

***ii*) How long does it take to get there (T1)?**

***iii*) What is the mechanism?**

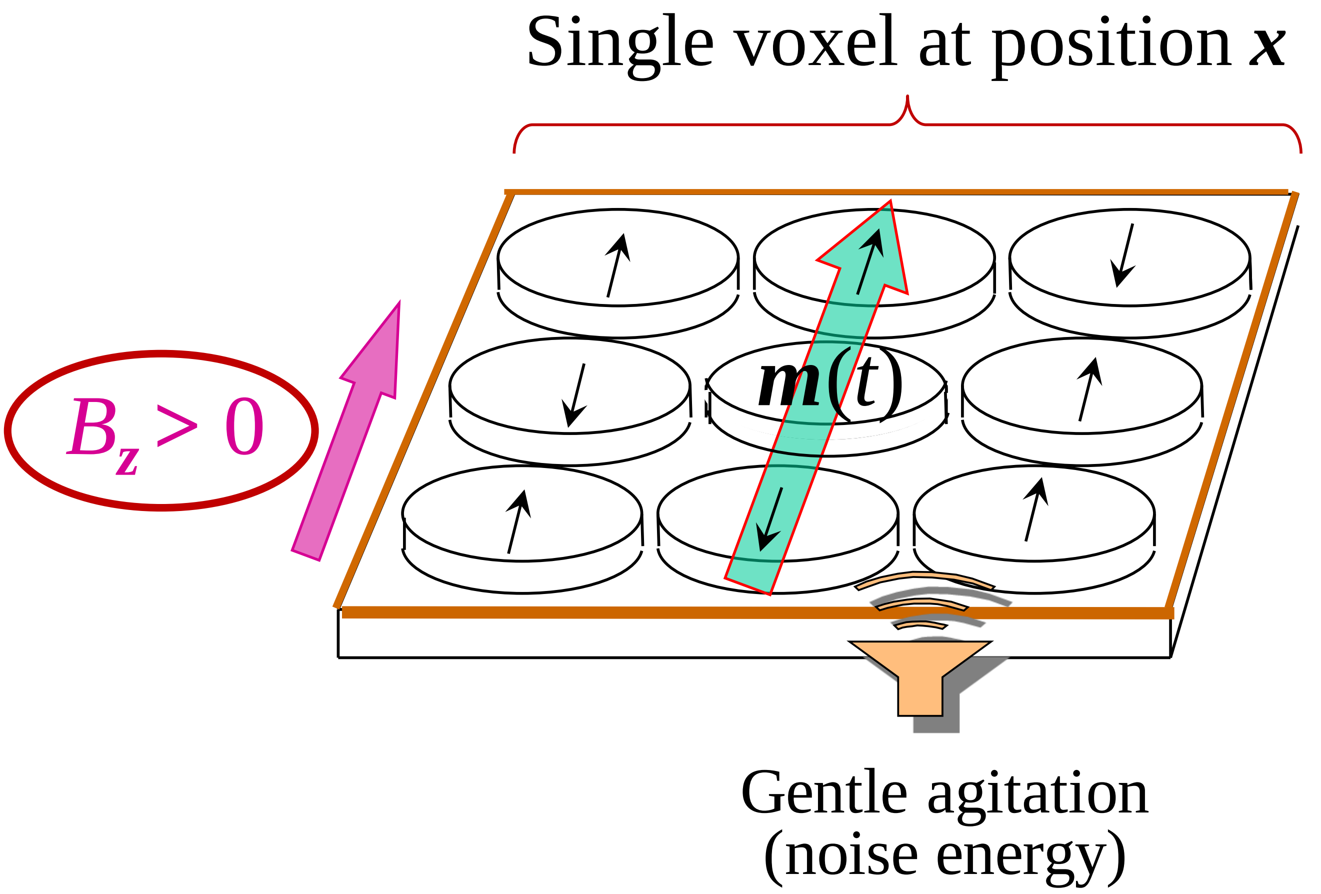
Ensemble of Compass Needles or Protons

$B = 0$



Magnetization, $\boldsymbol{m}(t)$, for the Voxel at Position $\boldsymbol{x}$:

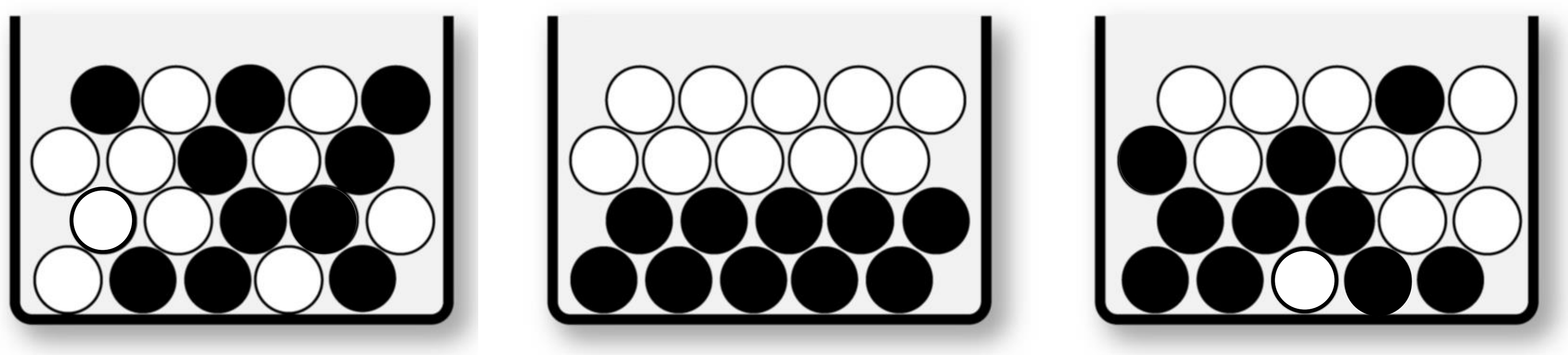
magnetic field *from* the ensemble of protons or needles *themselves*



Filling Four Energy Levels of Marbles *vs.* Noise Level

equilibrium from battle between energy and entropy

(all slippery; black balls denser)

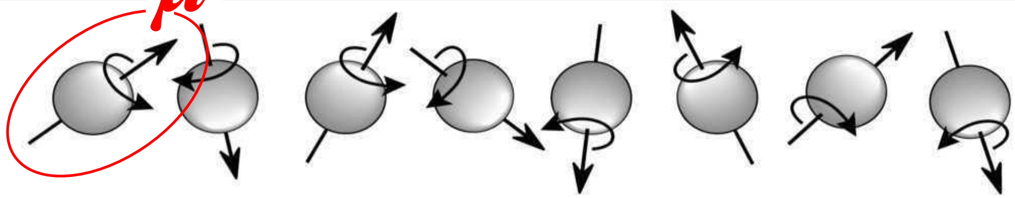
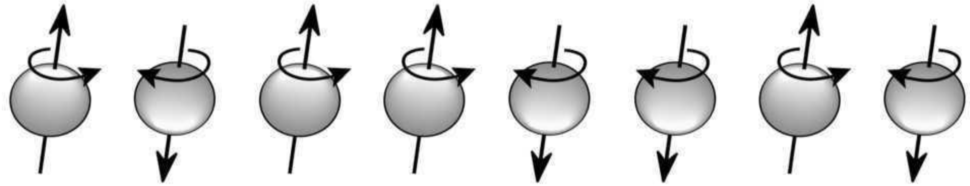
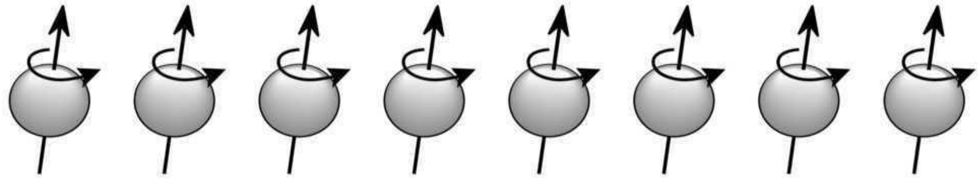
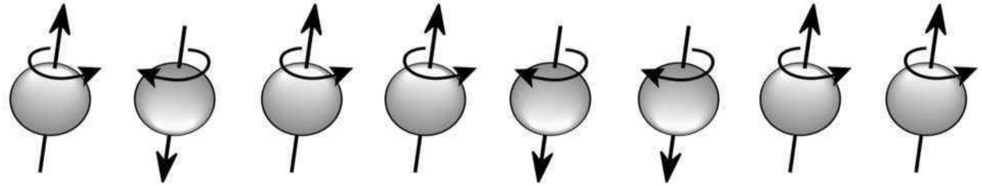


Shaking (Noise) Energy:

too much *too little* *just right*

Magnetization in Voxel at $\boldsymbol{x}$, under Dynamic *Equilibrium*:

$$\boldsymbol{m_0}(\boldsymbol{x},t) = [N_-(x,t) - N_+(x,t)]\times\boldsymbol{\mu}\ , \quad t \longrightarrow \infty$$

B_z	$\boldsymbol{\mu}$	$\boldsymbol{m_0}$
0 tesla		0
0.01 T *or* t = 0+*		~0
»1.5 T		$N\boldsymbol{\mu_z}$
1.5 T $t >> 0$		$5\times10^{-6}\,N\boldsymbol{\mu_z}$ (*Boltzmann*)

* after abruptly turning on $\boldsymbol{B_z}$, or after a 90º pulse.

RF Signal from Voxel, #1

Voxel's MRI signal is proportional to its magnetization, $\boldsymbol{m}(x,t)$

#1: $s(x) \sim \boldsymbol{m}(x,t) \sim \mathrm{PD}(x)$

T1 Proton-Spin Relaxation, in a Voxel

Voxel's MRI Signal Proportional to Its Magnetization, $\boldsymbol{m}(x,t)$

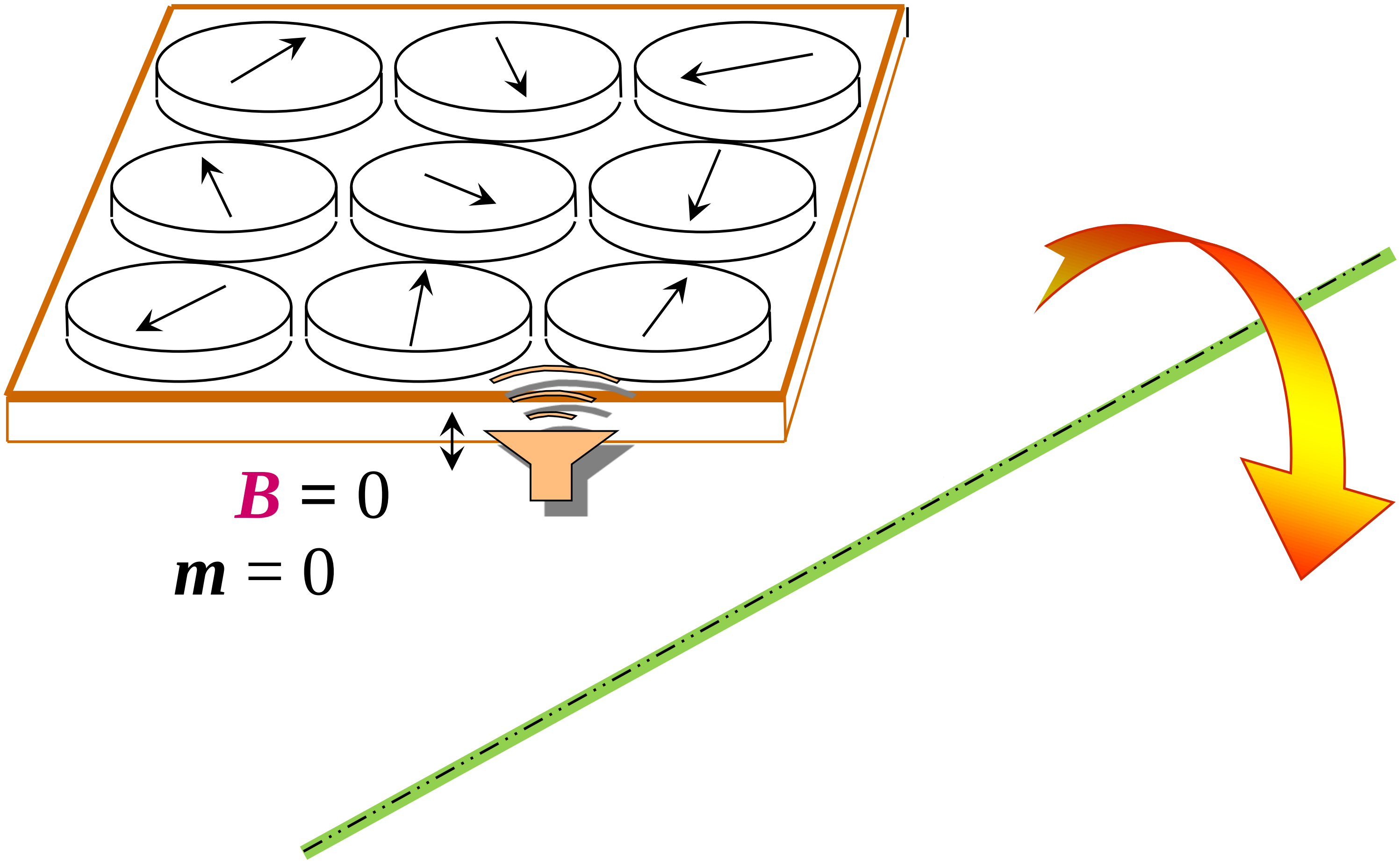
***i*) What is the magnitude of voxel magnetization at dynamic thermal equilibrium, m_0?**

***ii*) How long does it take to get there (T1)?**

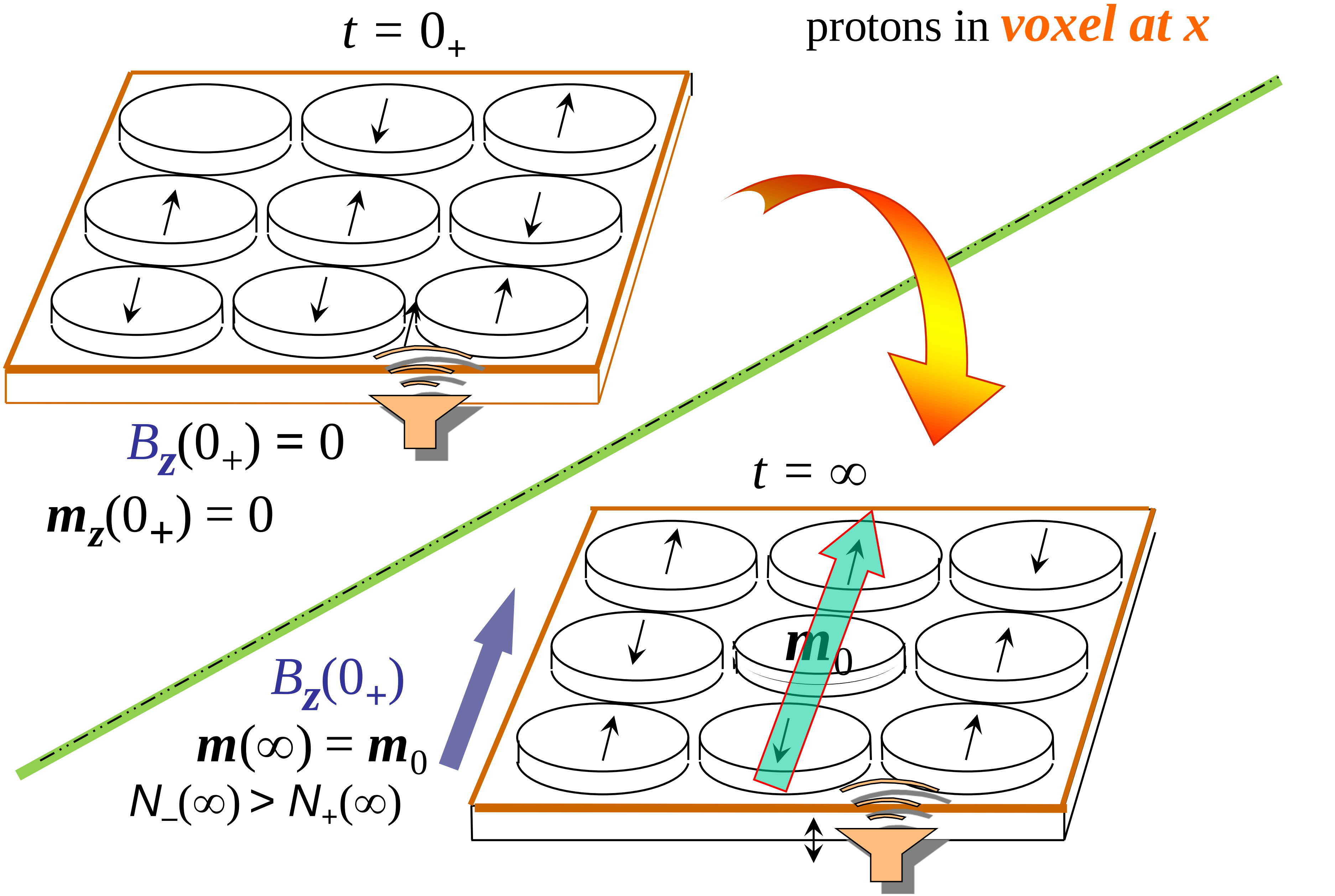
***iii*) What is the mechanism?**

Switching $\boldsymbol{B}_z$ On at $t = 0$ Induces Magnetization $\boldsymbol{m}(0_+)$

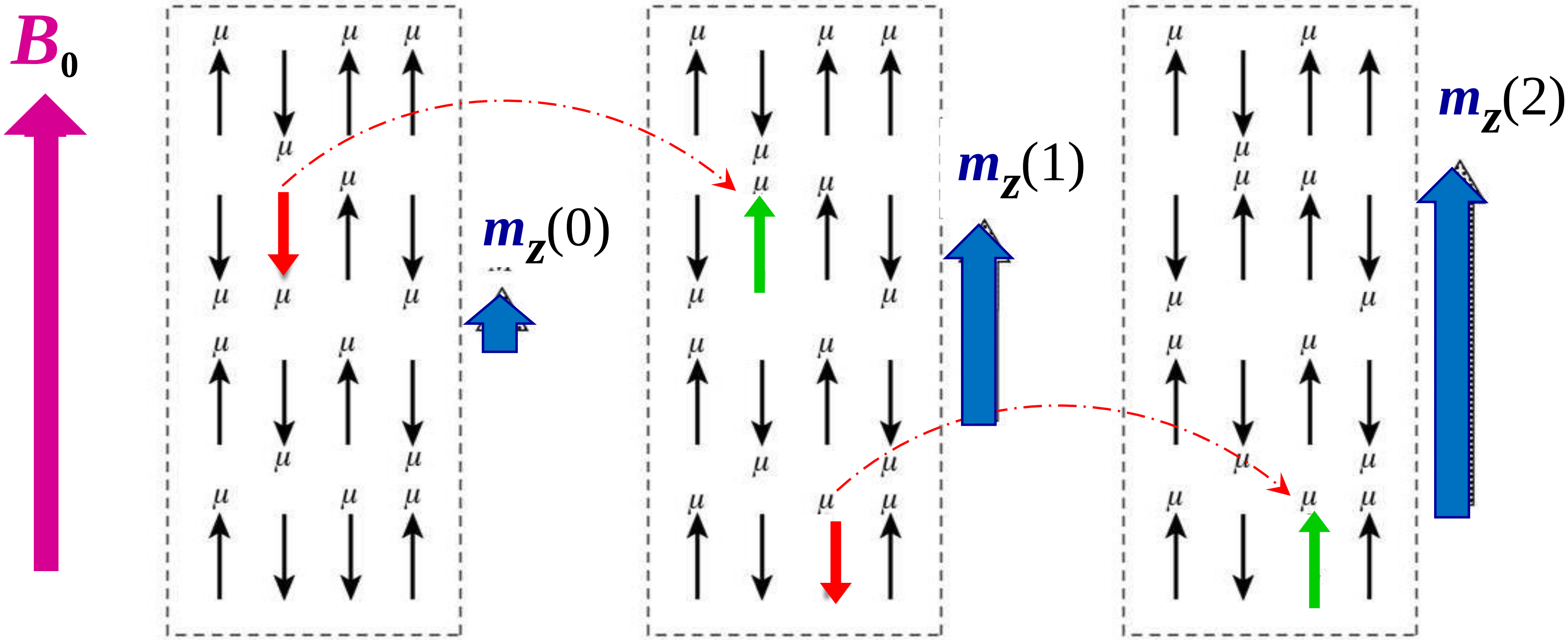
$t = 0\_$



Over Time, $\boldsymbol{m}(0_+)$ Moves from $\boldsymbol{m}(0_+)$ toward $\boldsymbol{m}_0$



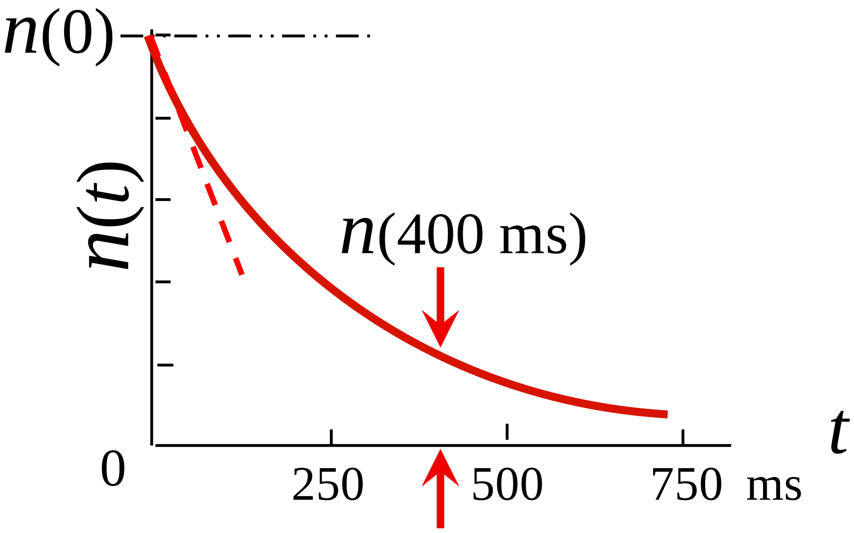
Polarization after t = 0



t = 0 ms | t = 1 ms | t = 2 ms

$m_z(t{=}0) = 0$ | $m_z(1) = 2\mu$ | $m_z(2) = 4\mu$

Aside: Exponential Decay of Radionuclide



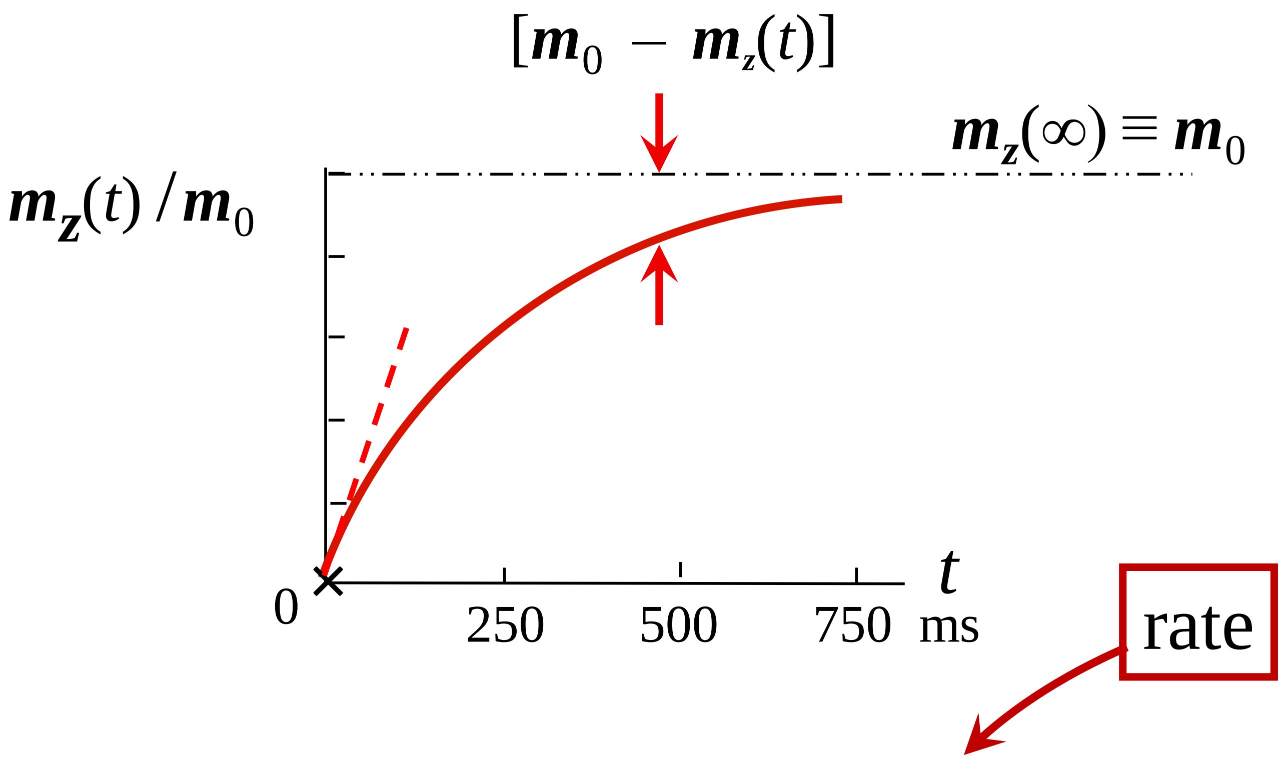
rate parameter

$$dn/dt = -\lambda\, n(t)$$

$$n(t)\,/n(0) = e^{-\lambda t}$$

photon atten. (x), tracer conc. (t), cell killing (D), *etc*.

Exponential Return of $\boldsymbol{m_z}(t)$ to Equilibrium Value, $\boldsymbol{m}_0$



$$d[\boldsymbol{m}_0 - \boldsymbol{m}_z(t)] / dt = -(1/T1)\,[\boldsymbol{m}_0 - \boldsymbol{m}_z(t)]$$

z-axis Bloch Equation

$$\boldsymbol{m}_z(t)/\boldsymbol{m}_0 = 1 - e^{-t/T1}$$

#2 T1, Regrowth of $\boldsymbol{m_z}(t)$ along $\boldsymbol{z}$-Axis

$$\textbf{\#2:}\qquad \boldsymbol{m_z}(t)/\boldsymbol{m}_0 = 1 - e^{-\,t\,/\,\mathrm{T1}}$$

Voxel's MRI Signal Proportional to Its Magnetization, $\boldsymbol{m}(x,t)$

***i*) What is the magnitude of voxel magnetization at dynamic thermal equilibrium, m_0?**

***ii*) How long does it take to get there (T1)?**

***iii*) What is the mechanism?**

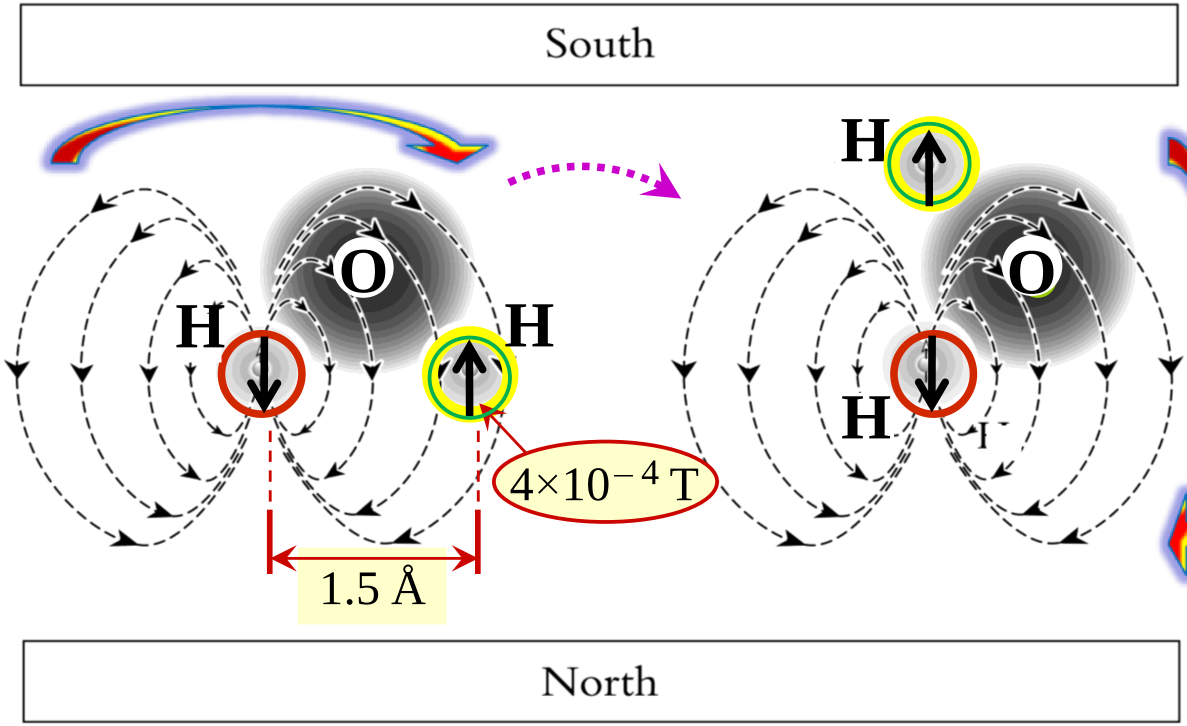
In MRI, the ***only*** thing a proton is ***ever*** aware of, or reacts to, is the ***local*** *magnetic field*, $\boldsymbol{B}_{\mathrm{local}}(t)$.

! ! ! ! !

In addition to $\boldsymbol{B}_0$ and $\boldsymbol{G}(t)$, the source of $\boldsymbol{B}_{\mathrm{local}}(t)$ can be either ***external*** ($\boldsymbol{B}_{\mathrm{RF}}$) or ***internal*** (*e.g.*, dipole-dipole from a moving partner-proton).

T1 Transitions: Magnetic ν_{Larmor} 'Noise'

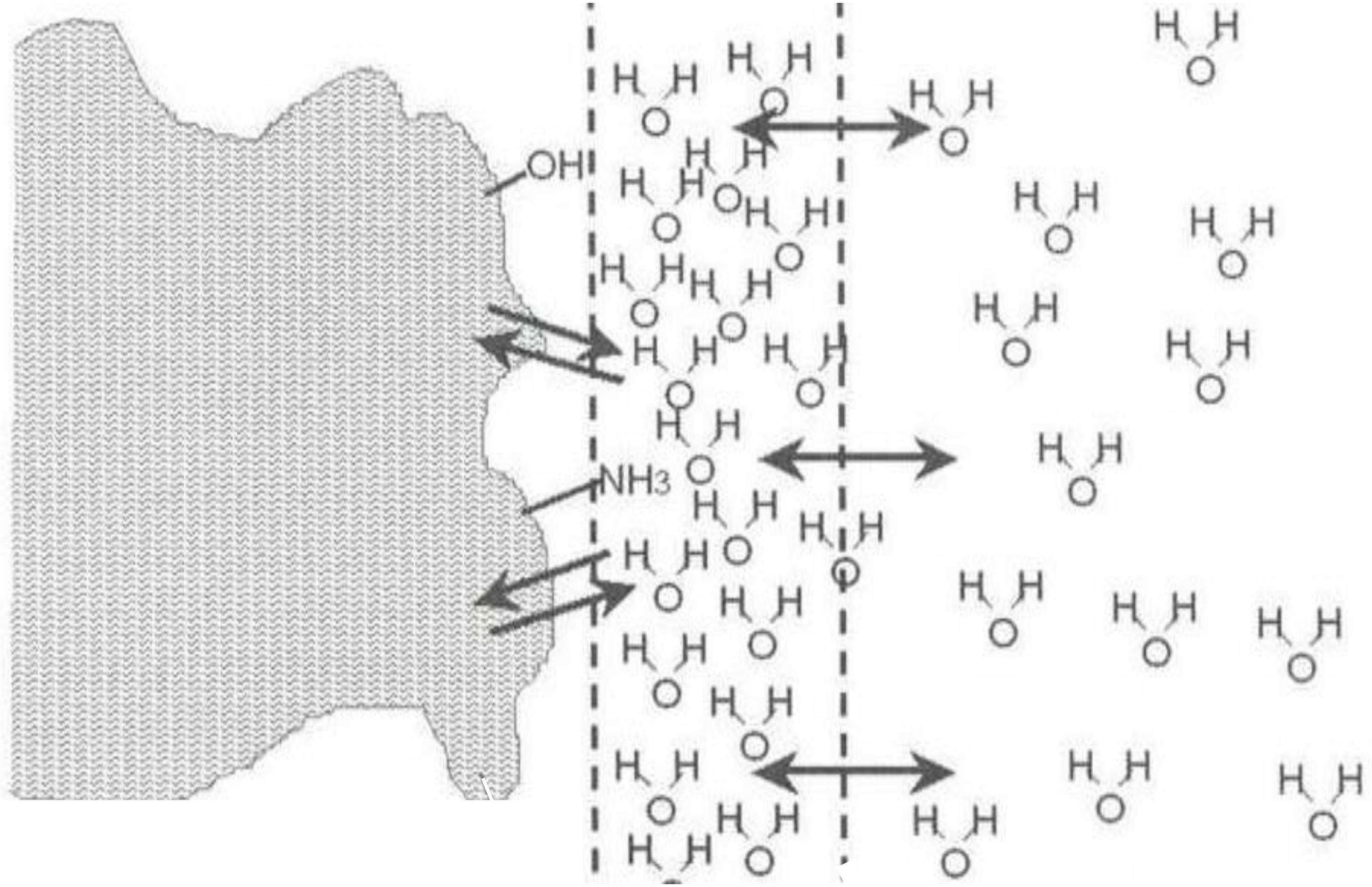
fluctuations in proton magnetic dipole-dipole interactions



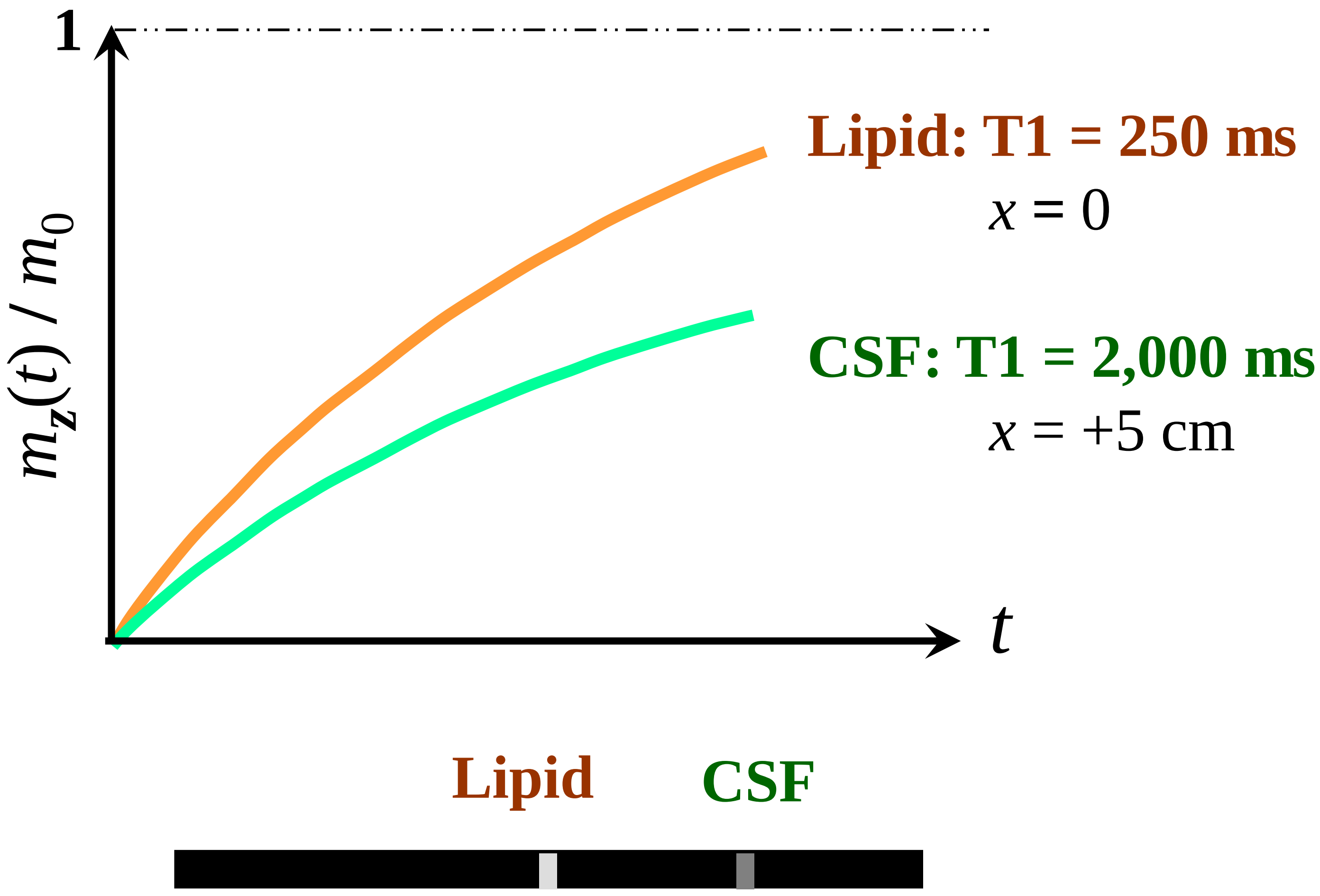
Each water proton produces *magnetic field fluctuations*
of all frequencies, including local $\nu_{\text{Larmor}}(x)$, at its **partner** proton

Factors Affecting $\boldsymbol{v}_{\text{Rotation}}$ of Water Molecule

more or less bound *hydration layer* *free*



Two Materials in 2 Voxels in 1D Phantom

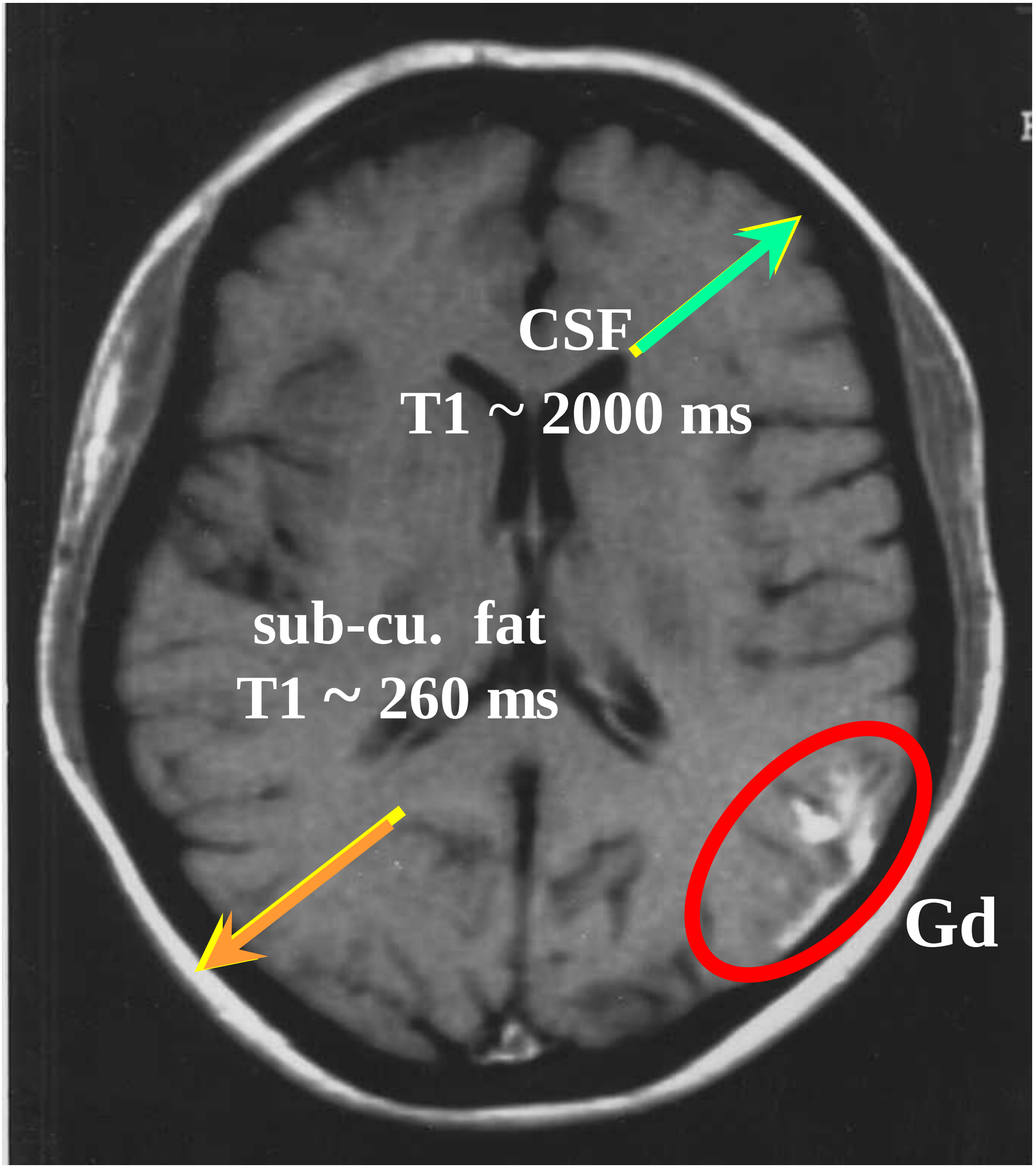


T1 MR image

Approximate Relaxation Times of Various Tissues

Tissue	PD p^+/mm^3, rel.	T1, *1 T* (ms)	T1, *1.5 T* (ms)	T1, *3 T* (ms)	T2 (ms)
pure H_20	1	4000		4000	4000
brain					
CSF	0.95	2000	2000	2000	200
white matter	0.6	700	800	850	90
gray matter	0.7	800	900	1300	100
edema			1100		110
glioma		930	1000		110
liver			500		40
hepatoma			1100		85
muscle	0.9	700	900	1800	45
adipose	0.95	240	260		60

T1-*w* MR Image



MRI Case Study, and *Caveat*

with T1, FLAIR, MRS, DTI, *f* MRI,
and MR-guided biopsy studies of a glioma

Case Study

57 year old ♀ medical physicist has had daily headaches for several months. Responds to ½ Advil.

Physical examination unremarkable. Patient appears to be in good general health, apart from mild hypertension, controlled by medication.

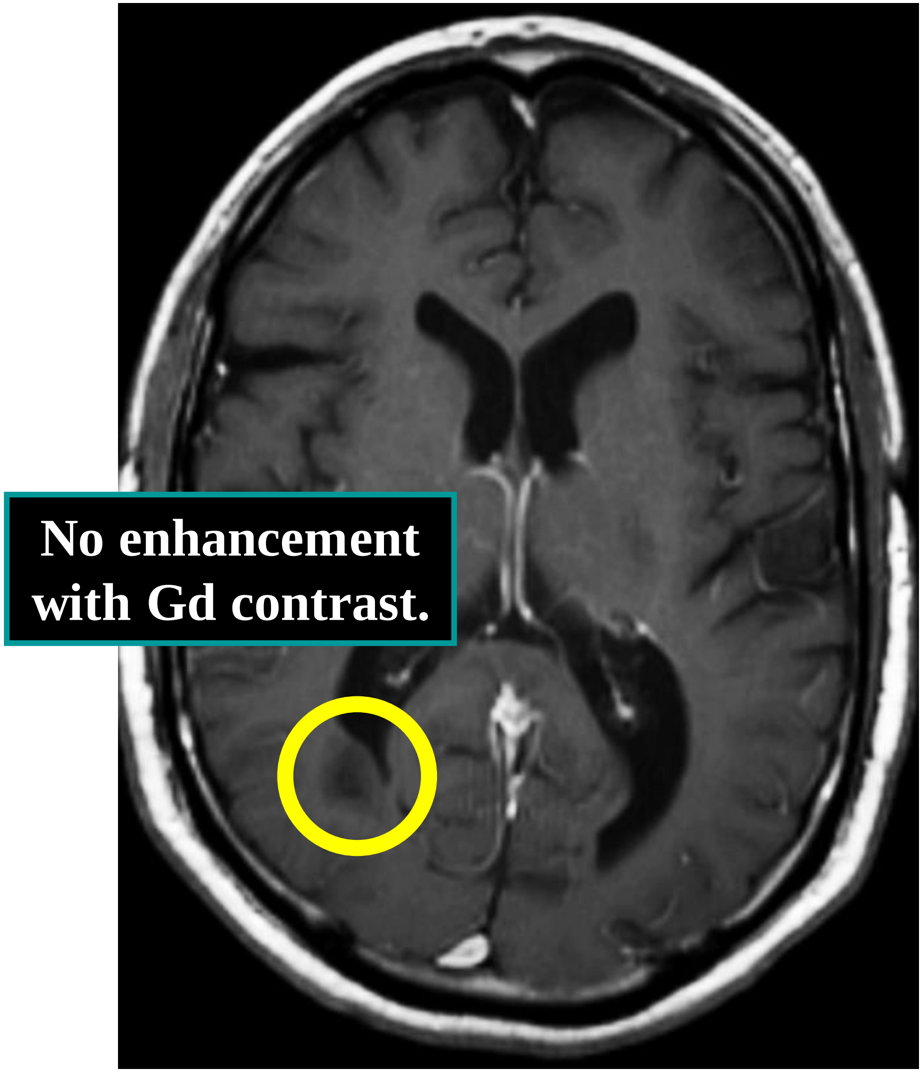
Good diet, exercises moderately. Patient reports no major stresses, anxieties.

CT indicates a lesion in the *right posterior temporo-occipital* region, adjacent to *occipital horn of right lateral ventricle*. MRI for better contrast.

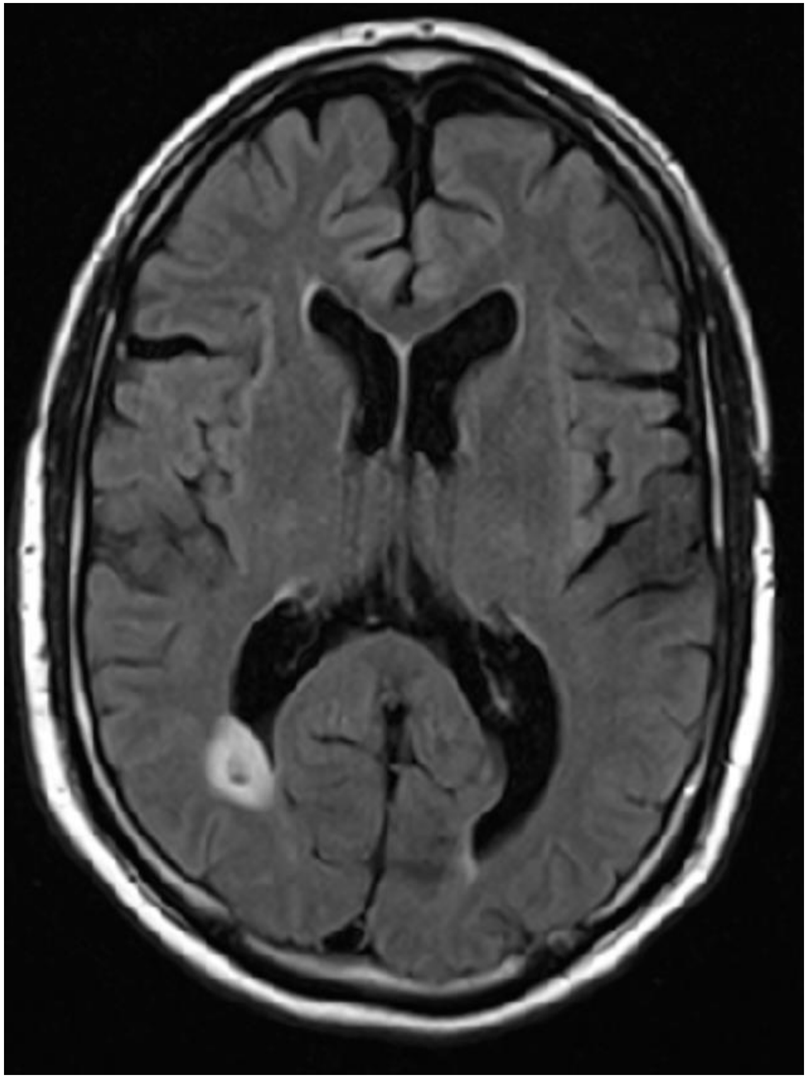
Principal concern: *Vision for reading*.

Lesion: Right Posterior Temporo-Occipital Region,

adjacent to occipital horn of right lateral ventricle



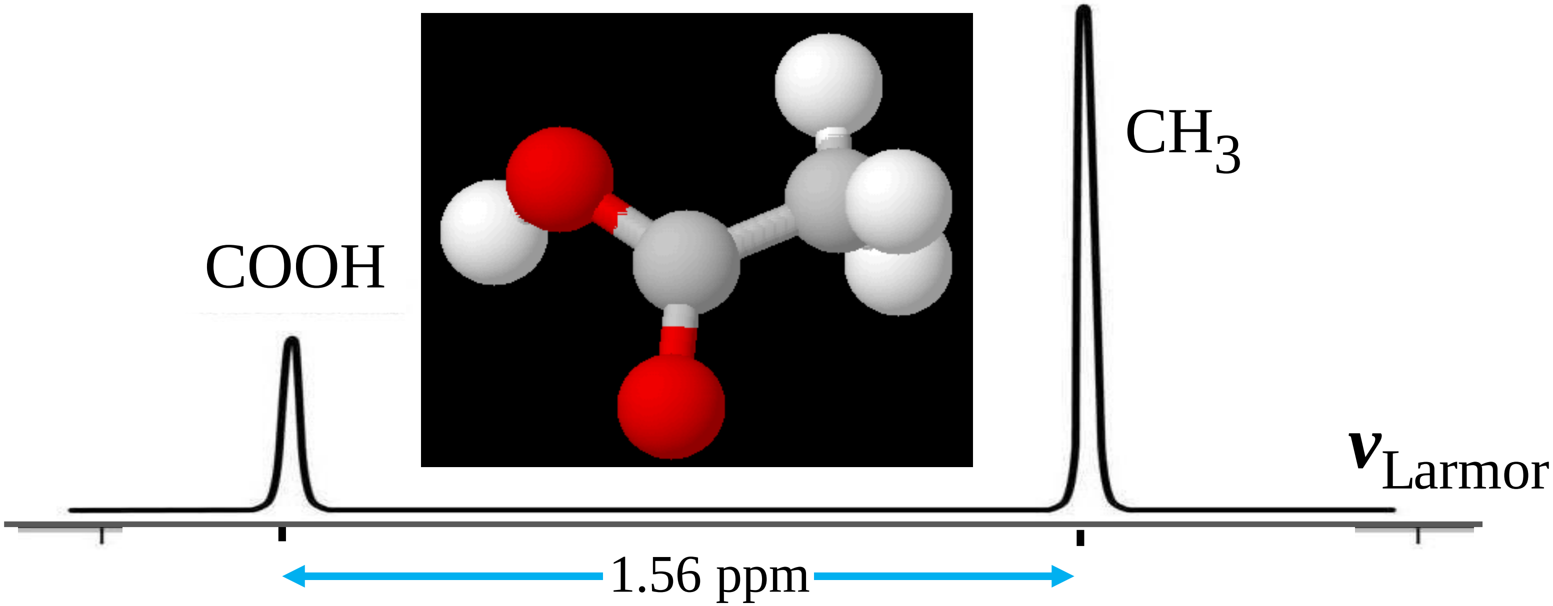
T1-*w*

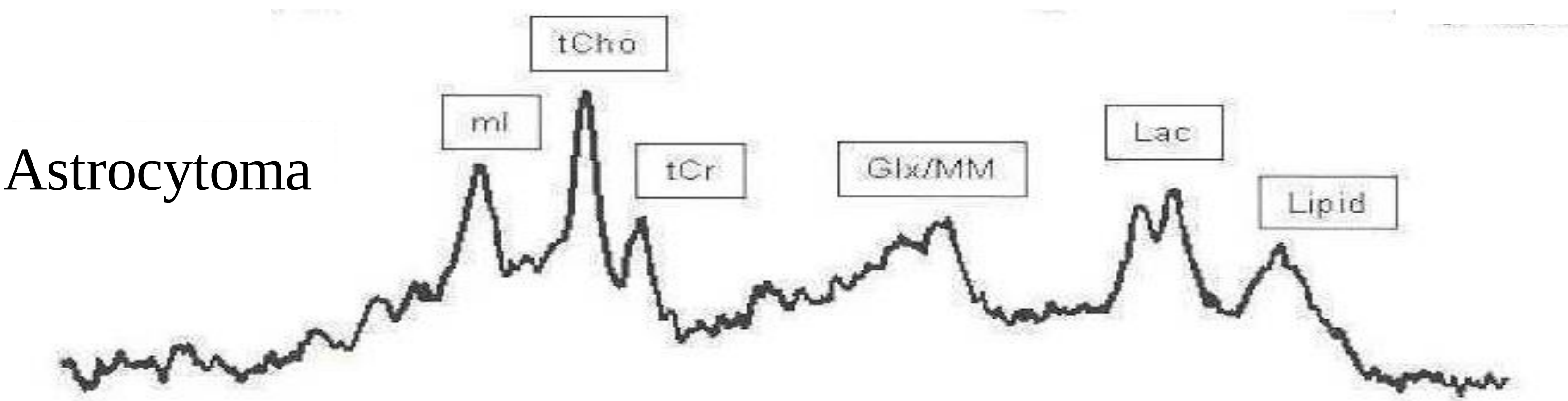


T1-*w* FLAIR

Chemical Shift and Non-invasive MRS ‘Biopsy’

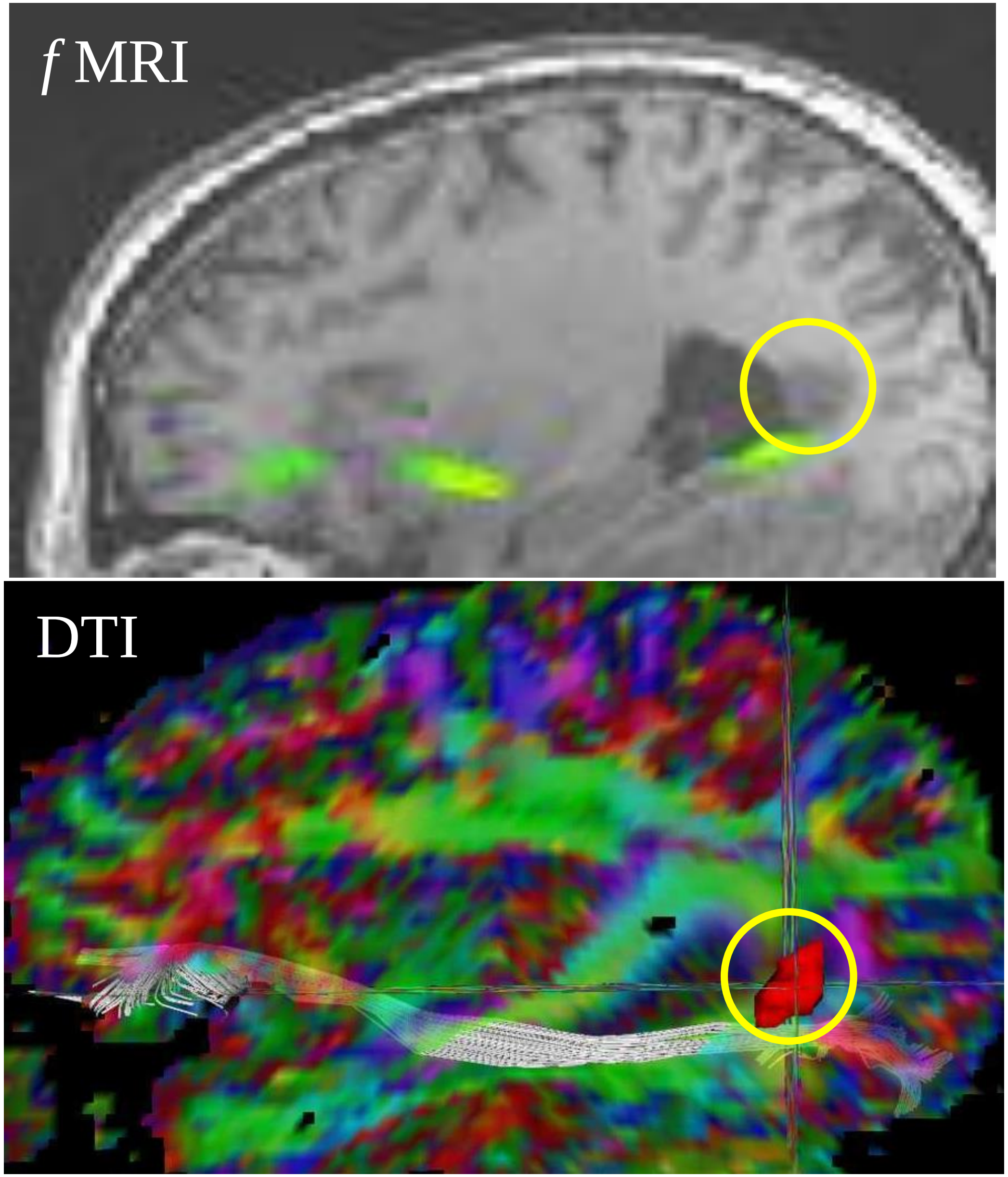
acetic acid



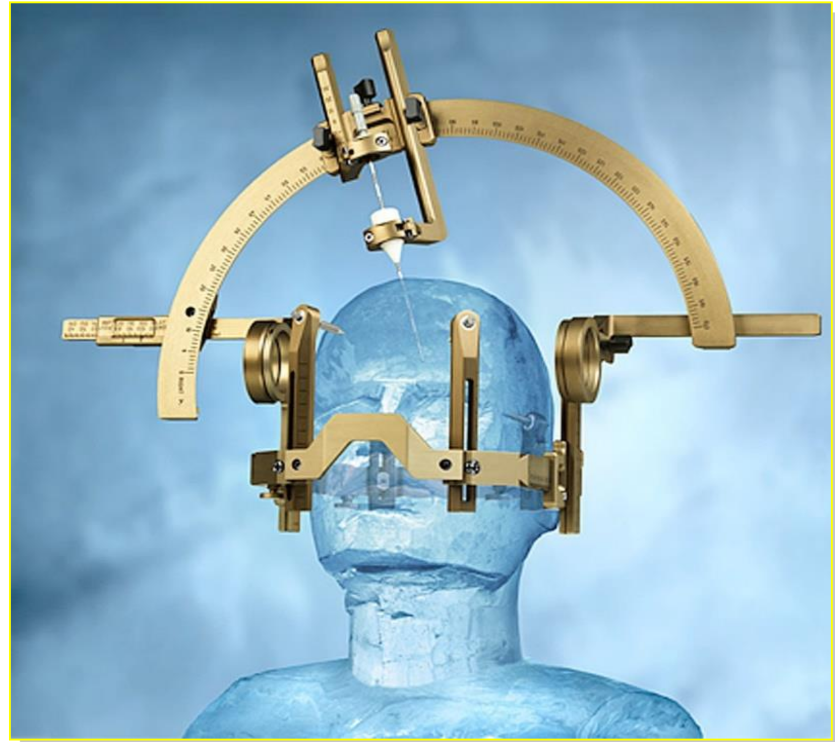


Functional MRI and Diffusion Tensor Imaging

visual stimulus



MRI-Guided Stereotactic Fine-Needle Biopsy



Caveat:

strong gradient fields outside bore

within / with patient, others	*in / into imaging suite*
aneurysm clip, shrapnel	O_2 tank, IV pole
cochlear implant, prostheses	wheelchair, gurney
artificial heart valve	hemostat, scalpel, syringe
stent, permanent denture	scissors, pen, phone, laptop
defibrillator, pacemaker	tool, tool chest
electrodes, neurostimulator	cleaning bucket, mop
medical infusion pump	fire extinguisher, ax
drug-delivery patch, tattoo	gun, handcuffs